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Revision A
January 1972

ROCKET EXHAUST PLUME COMPUTER PROGRAM IMPROVEMENT

USER'S MANUAL
VARIABLE C/F RATIO METHOD
OF CHARACTERISTICS PROGRAM
FOR NOZZLE AND PLUME ANALYSIS

by
S. D. Smith
A. W. Ratliff


G. D. Reny, Manager
Aeromechanics Department

George D. Perry
for J. S. Farrior
Resident Director

FOREWORD

This document presents the results of work performed by the Fluid Mechanics Section of the Aeromechanics Department of Lockheed's Huntsville Research & Engineering Center. This report is Volume I of a four-part final report, as required to fulfill Contract NAS7-761. This work was sponsored by the Liquid Propulsion Section of Jet Propulsion Laboratories, Mr. Wolfgang Simon, Technical Manager.

This document constitutes Volume IV of a four-part final report. The other three volumes, printed separately, are:

Volume I — "Summary Volume — Method of Characteristics Plot Program," LMSC-HREC D162220-I

Volume II — "User's Manual — Method of Characteristics Plot Program," LMSC-HREC D162220-II

Volume III — "Solution of Non-Isoenergetic Supersonic Flows by the Method of Characteristics," LMSC-HREC D162220-III.

REVISION NOTICE

Lockheed Missiles & Space Company, Inc., Huntsville Research & Engineering Center Technical Report HREC-7761-I (D162220-I), entitled "User's Manual — Variable O/F Ratio Method of Characteristics Program for Nozzle and Plume Analysis," dated June 1971 is revised as indicated below,

Revision A changes the document number from HREC-7761-I, D162220-I to HREC-7761-4, D162220-IV.

Revision A affects title page and pages ii, 2-3, 2-4, 2-6, 2-7, 3-2, 3-3, 3-4, 3-5, 3-7, 3-9, 3-10, 3-11, 3-13, 3-15, 3-16, 3-17, 3-22, 3-24, 3-25, 3-26, 3-56, 3-71, 4-1, A-15, A-16, A-17

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SYMBOLS AND NOTATIONS

Symbol	Description
M	Mach number
R	"gas constant"
R, r	radial coordinate
X, x	axial coordinate
y	normal coordinate
P, p	pressure
T, t	temperature
S, s	entropy
V, v	velocity
\dot{M}	mass flow
A/A^*	area ratio
\dot{w}	weight flow
A	area
γ	isentropic exponent
δ	turning angle through shock
ϵ	shock angle
θ	flow angle
μ	Mach angle
β	characteristic angle
ρ	density
λ	equation modifier
ψ	operation function
ϕ	point description information
Subscripts	
∞	freestream conditions
o	stagnation conditions
B	boundary conditions

Section 1
INTRODUCTION

A precise knowledge of local flow properties in nozzles and exhaust plumes is necessary for performance, radiation, attenuation, heat transfer and impingement analyses. All of these analyses are dependent on an accurate knowledge of the environment.

Lockheed Missiles & Space Company, Huntsville Research & Engineering Center has developed, under the sponsorship of several governmental agencies, a two-dimensional or axisymmetric method-of-characteristics program. The program is applicable for problems involving supersonic flow of an inviscid, adiabatic reacting gas in thermal equilibrium.

Areas of particular interest are modifications to the existing program to expand the capabilities and flexibility of the program. In particular the capability to handle O/F gradients within the flowfield has been incorporated.

As a preliminary step in the plume analysis, an accurate knowledge of the nozzle flow field is required. Both nozzle and plume calculations are performed with the same program. This program is a versatile, user-oriented, analytical tool which is capable of producing all of the gas dynamic nozzle or plume data required for an impingement analysis. The user may choose a solution for a

1. nozzle only,
2. plume only,
3. combination nozzle and plume,

depending on the options and starting data selected. This program has been in use for several years and experience has led to a continual refinement of the calculational procedure.

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This document was prepared to facilitate operation and understanding of the program. Descriptions of the individual routines are presented. Answers to any questions pertaining to the operation of the program should be found in this document or in the program listing. Questions involving initial assumptions made in applying the general theory can be answered by referring to Volume III of this document or to the Appendix.

Section 2 PROGRAM CAPABILITIES AND APPLICATIONS

2.1 CAPABILITIES

The nozzle and plume computer program described in this document can be used to solve a wide variety of problems in real gas, supersonic, compressible flow. Capabilities were previously discussed in Ref. 1; however, as improvements continue to be made to the basic program new capabilities evolve. Some of the more important, basic capabilities of the existing program are outlined below:

- The gas may be ideal or real. If real, frozen or equilibrium assumptions can be made. Oxidizer/fuel gradients may be considered.
- Two-dimensional or axisymmetric problem geometry can be used.
- Both upper and lower boundaries can be solid or free. (A solid boundary can be approximated by either a conic or polynomial equation.)
- A nozzle wall may be curve fit with discrete points.
- One compression corner on the upper wall can be calculated. (Any number may be considered if the problem is re-started each time.)
- The number of Prandtl-Meyer rays to be computed around expansion corner discontinuities may be input.
- Any number of expansion corners can be considered on either the upper or lower wall.
- Various methods for obtaining an initial start line are utilized.
 1. The program will calculate a one-dimensional start line anywhere in the nozzle.
 2. The program will calculate a start line at points within the nozzle necessary to conserve mass.
 3. Characteristic data can be input at points across the flow field within the nozzle or in the plume.

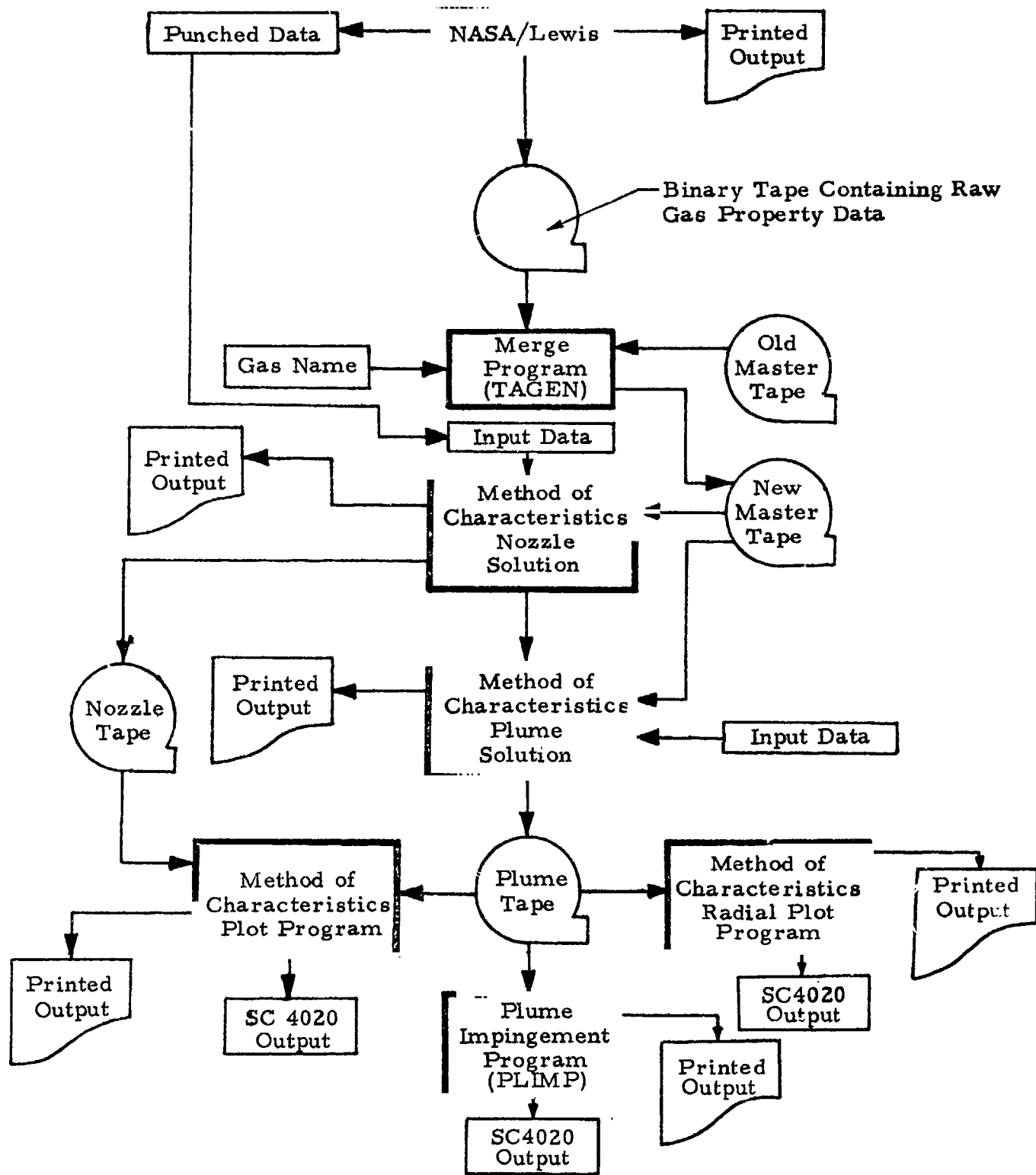
4. Any right running characteristic line can be used for a start line. (See page 2-10.)
 5. Any left running characteristic line can be used (may be in combination with a normal start line). (See page 2-10.)
 6. Any left running line may be input with a right running shock crossing it. (See page 3-15.)
- Hypersonic or quiescent approach flow options may be used.
 - Exit to ambient pressure ratios from over expanded to highly under expanded are possible.
 - Viscous boundary layer approximations at the nozzle lip are available. (See page 3-25 and Appendix.)
 - Displacement of the axis of symmetry from the center of flow (i. e., the plug nozzle flow field) is possible.

Reacting gas solutions have been facilitated by modifying the Chemical Equilibrium Composition Program (CEC) (Ref. 2) to provide binary tape and punched output of its equilibrium or frozen real gas calculations at any desired O/F ratio(s). The Method-of-Characteristics program has the capability for selecting the proper case from a large set of real gas properties cases stored on a master tape. Lockheed/Huntsville's master tape presently consists of approximately 70 cases and is continually being expanded. The method of generating this master tape is outlined in the diagram on the following page. Cases stored are uniquely identified by some characteristic of the particular gas under consideration. For example, a LOX/LH₂ system may be identified by the following:

<u>Gas Type</u>	<u>Mixture Ratio</u>	<u>Chamber Pressure</u>
O ₂ /H ₂	O/F = 1.5 - 8.0	PC = 546.0

New cases of general interest may be added to the master tape; however, ad hoc cases should be prepared on a separate tape. Tape preparation sequence and communication with the Method-of-Characteristics program is diagrammed on the following page.

Once the method-of-characteristics solution has been obtained, the output tape may be used to map the flowfield using the method of characteristics



Plot Program described in Volume III. The output tape may be used by the Method-of-Characteristics Radial Plot Program (Ref. 3) which determines the radial variations of flowfield properties across the nozzle and plume flowfields at constant axial stations. The Plume Impingement Program (PLIMP) (Ref. 4) may also be run to determine the effects of the rocket exhaust plume on objects immersed in the plume. Sequencing and communication of auxiliary programs with the Method-of-Characteristics program is on the preceding page.

Two-dimensional or axisymmetric solutions are selected by simply loading a control word in the program input data. This integer (0 or 1) is then multiplied by the term containing $(1/r)$ in the governing differential equation. By appropriate description of the flow boundaries, it is possible to change from a solid to free boundary on either the upper or lower walls. Conversely, it is not possible to change from a free to a solid boundary on either wall.

Compression corners are allowed only on the upper wall. Because the program is restricted to a single shock within the flow field, the number of compression corners is limited to one. Also, right-running shocks only can be handled, thus no provision exists for compression corners on the lower wall. Remembering that a mirror image solution is possible, the problem can be inverted for this type of solution. Note that the program will fortuitously handle two shocks if the first shock terminates by intersecting a lower free boundary before the second shock begins.

By choosing an input option, it is possible for the program to automatically reflect a shock which intersects the horizontal axis. The method is illustrated in Section 2.2 and explained in the Appendix.

When a shock intersects the horizontal axis and the automatic reflection option has not been flagged, the solution may be restarted by inverting the problem and "regularly" reflecting the shock. A shock is "regularly" reflected by inverting the problem and using start line options to initiate the reflected shocks (Sections 2.2, 3.1.1 and 3.1.2). When a restart is required for a shock which has terminated at a "Mach Disc," a boundary equation simulating a cylindrical "pipe" must be used to approximate the subsonic region (Section 2.2).

Problem solid boundaries can be described by a set of discrete points. The set of points is spline fit with individual polynomials for each pair of points, consistent with the polynomial boundary specification option of the program. Specific usage instructions for this option are included in the input Section (3.1.1).

Shock wave calculations may be discontinued when the shock strength decreases to an insignificant value. The shock will continue to be calculated in its usual manner until the change in stagnation pressure becomes less than a given input percentage. After the criterion is satisfied, the shock will no longer be iterated. If a value for the percentage change is not provided in the input, the shock will be computed in its usual manner until the percentage change drops below 0.1. (See Section 3.1.1 for description of input for this option.)

The program computes nozzle thrust by integrating the pressure distribution along the nozzle wall, including the thrust increment between the last characteristic line inside the nozzle and the Prandtl-Meyer expansion at the nozzle lip. The vacuum specific impulse and nozzle thrust coefficient at each nozzle wall point is also calculated.

A mesh control option exists whereby the maximum and minimum characteristic mesh size can be controlled by input to the program. Mesh control increases program accuracy in large vacuum plume calculations. A description of mesh control is contained in the Appendix.

The streamline at each characteristic data point is calculated and stored on the output tape.

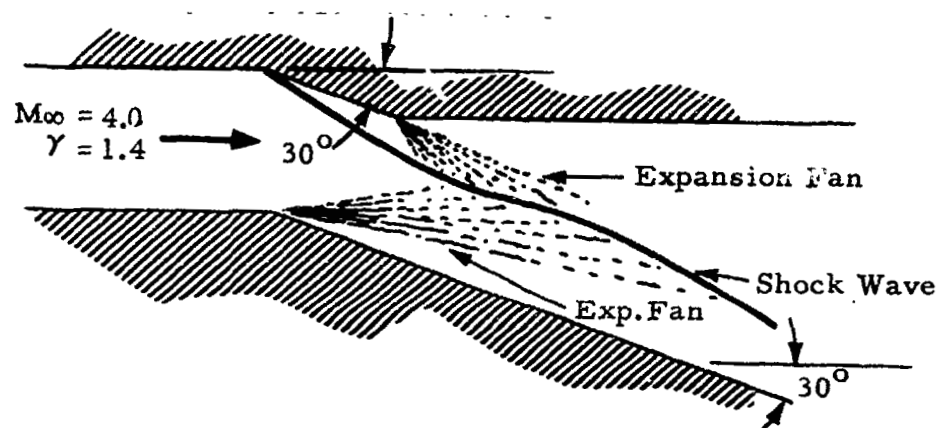
2.2 APPLICATIONS

The most common applications of this program are in the areas of standard rocket nozzles and axisymmetric plumes. Many other complex flow fields can be treated, however, if the user is familiar with the flexibility of

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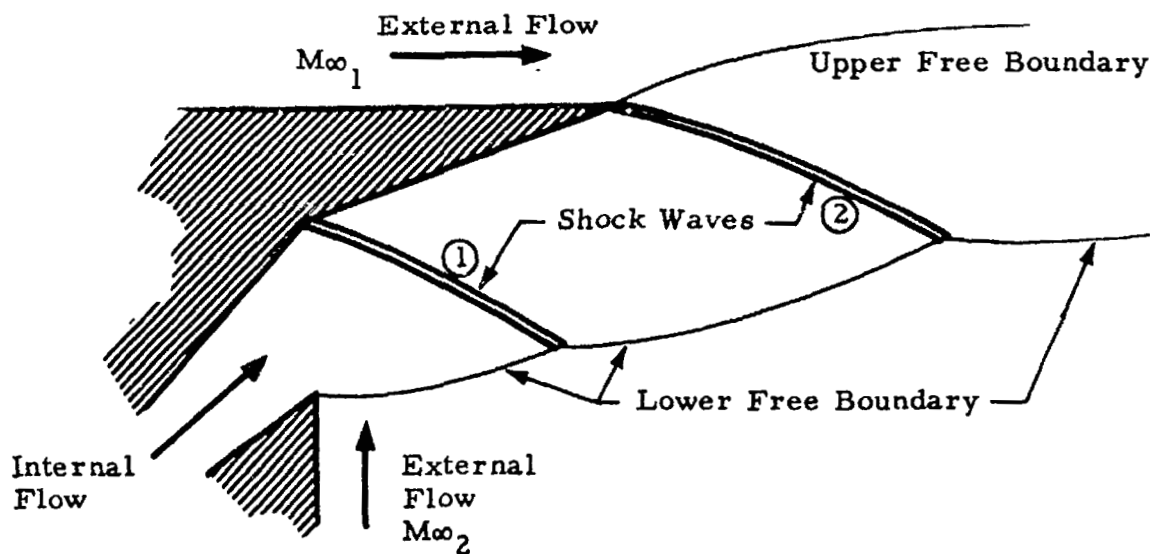
the program and its options. Several problems are discussed in the remaining paragraphs of this section to illustrate the versatility of the program.

Consider the boundary conditions given below. This problem was run two-dimensionally (although it could just as well have been axisymmetric) for the purpose of program demonstration.



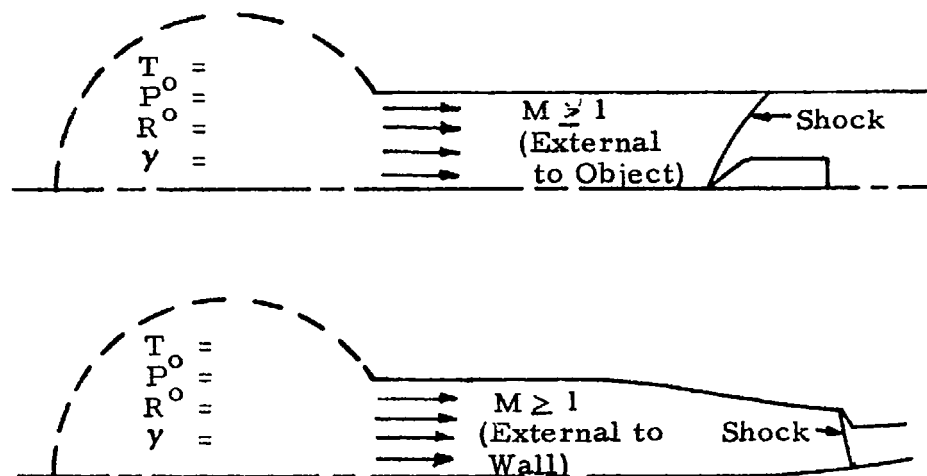
The problem above, while being restricted to one compression corner, could have had more expansion corners illustrating a more complex case.

Another problem depicting the program's versatility is the following:



The restriction that the flow remain supersonic (inherent in the method-of-characteristics solution) must be observed through the flow field.

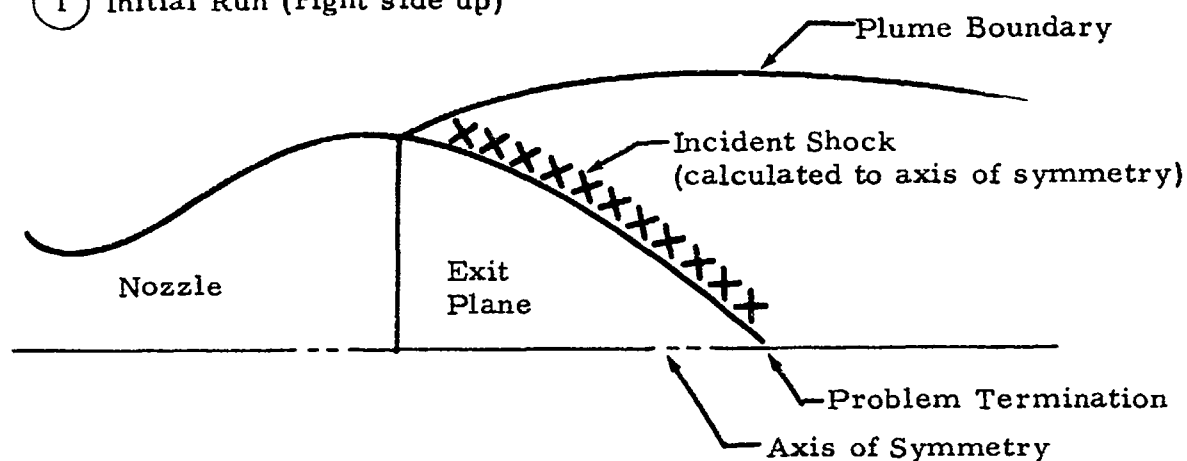
External flow can be simulated by specifying the necessary stagnation conditions and inserting a two-dimensional or axisymmetric object in the flow field.



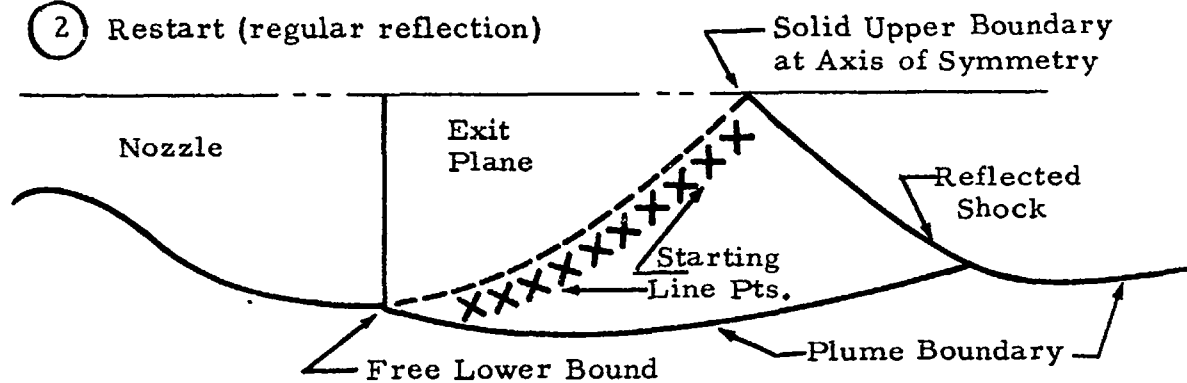
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The method of manually reflecting a shock "regularly" or through a "Mach reflection" is outlined below.

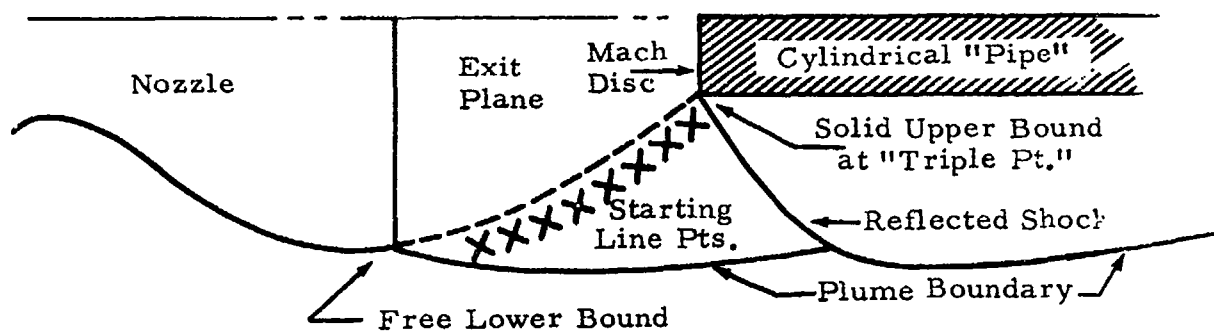
① Initial Run (right side up)



② Restart (regular reflection)

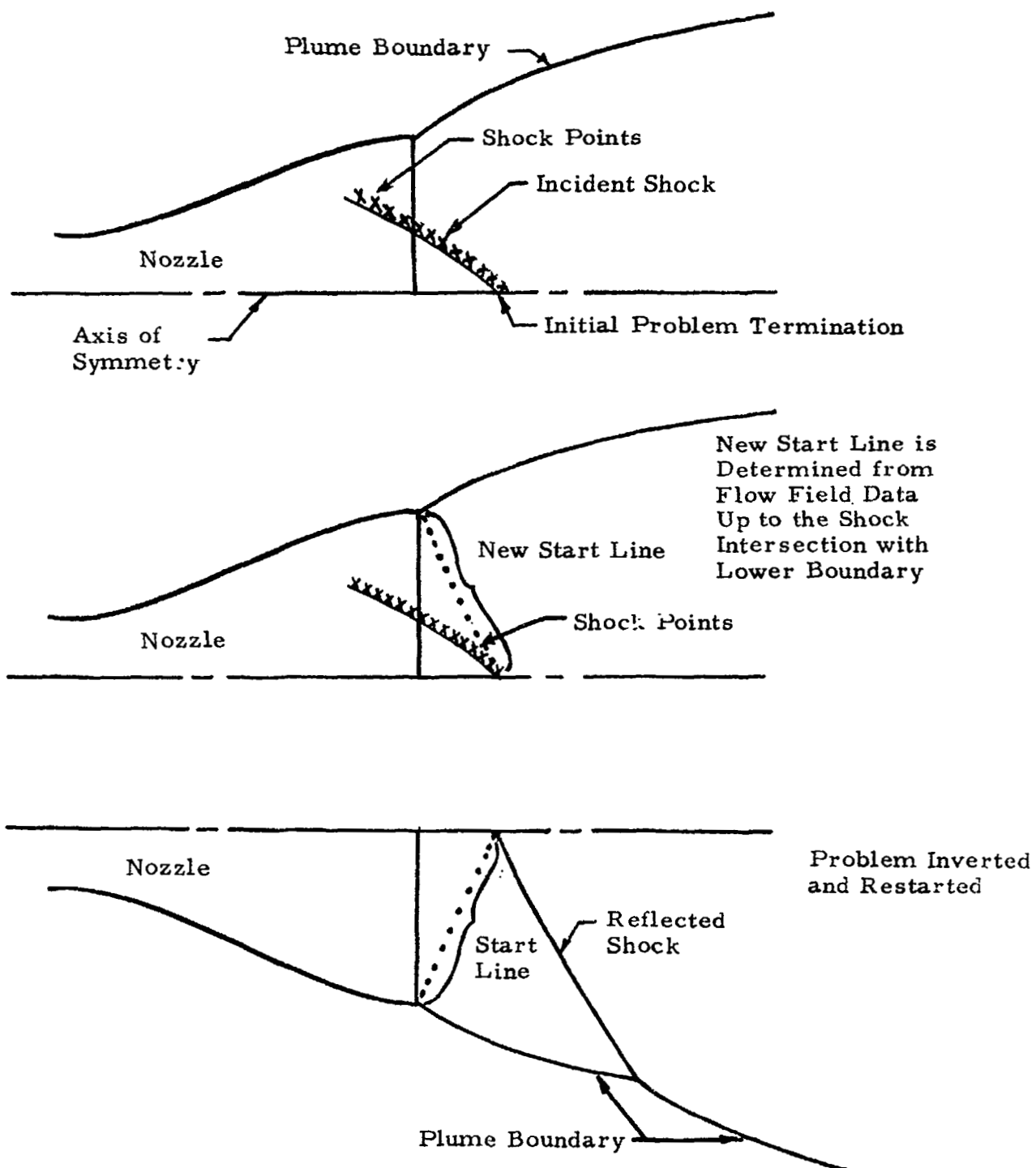


③ Restart (Mach reflection)

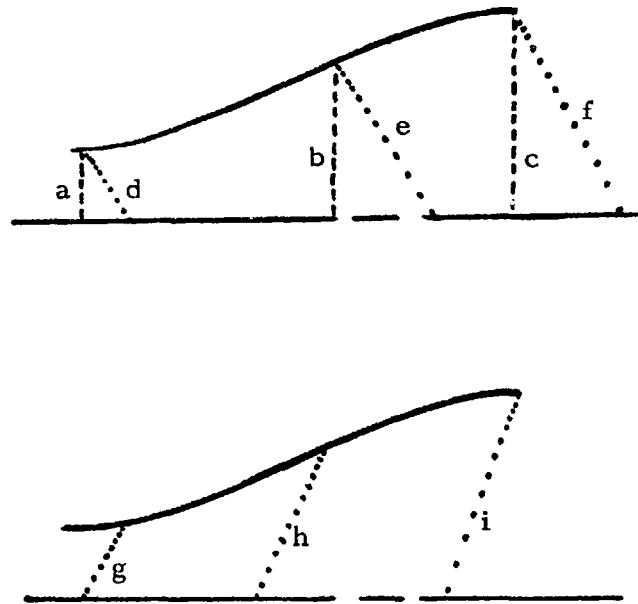


When the automatic reflection option is selected and a shock terminates at the lower boundary the program will automatically reflect the shock as outlined in the diagrams below.

Example of Automatic Restart



The subsequent sketches illustrate the start line options available to the user to begin the method of characteristics solution. Lines a, b and c are normal start lines obtained by specifying the same axial location of the upper and lower limits of the start line. Lines d, e and f are right-running start lines obtained by specifying different locations of the upper and lower limits of the start line. Lines g, h and i are left-running start lines. All three types of start lines may be input or calculated by specifying the Mach number along the start line, the area ratio (A/A^*) at the start line, or by using conservation of mass and the Mach number at the upper wall. Lines a, d and g may not be calculated by area ratio since they initiate from the nozzle throat.



The options available to manually input a start line for a reflected shock case are explained and illustrated in Section 3.1.2 (ICON(9)).

Section 3 DISCUSSION

The program consists of 66 active subroutines and functions which perform all the required calculations in the nozzle and plume. This building block approach simplifies troubleshooting, operation and modifications. Each of the 66 routines is explained separately. In addition, a general flow chart (Fig. 3.1) , and a breakdown of the routines according to function are presented.

The input instructions and description of the Input FORTRAN symbols are covered in the input section. The output interpretation is covered in the output section. Also included is a list of all the common block variables along with a definition or use of each variable.

3.1 INPUT INSTRUCTIONS

This subsection contains a detailed description of the program input instructions as follows:

- Detailed input guide
- Detailed description of the input FORTRAN symbols

3.1.1 Detailed Guide for Input Data to MOC-O/F Program
(Section 3.1.2 contains a detailed description of each of the input variables)

<u>CARD NO. 1</u>	<u>Problem Title or Identification</u>	
Format:	12A6	
Cols. 1-72	HEADER(I)	Comment card, header information such as problem title may go on this card. It is printed at the top of each page of output.
<u>CARD NO. 2</u>	Run Control Card	
Format:	16I5 (right adjusted)	
Col 5	ICON(1)	1 Read cards for gas properties 2 Read tape 10 (A6) for gas properties
Col 9	ICON(2)	0 Regular start line (other than right or left running) 1 Right-running characteristic start line 2 Left-running characteristics start line
Col 10	ICON(2)	0 Straight start line M given 1 Source start line A/A^* given 2 Starting line input 3 Starting line calculated by conservation of mass using a linear Mach number distribution
Cols 14, 15	ICON(3)	Number of starting line points (50 max)
Cols 18-20	ICON(4)	Number of upper boundary equations including free boundary equation (100 max)
Option for ICON (4) when upper boundary is to be curve fit		
Cols 17-20	ICON(4)	1000 + number of discrete points specifying upper boundary + 2, where the 2 represents the nozzle throat equation and the free boundary equation
Cols 23-25	ICON(5)	Number of lower boundary equations (100 max)
Option for ICON(5) when lower boundary is to be curve fit		
Cols 22-25	ICON(5)	1000 + number of discrete points specifying lower boundary + 2, where the 2 represents the nozzle throat equation and the free boundary equation.
Col 27	ICON(6)	0 The start line will not be output on punched cards 1 The start line will be punched on cards in the form of Card 9. (This start line can be used to manually restart an "automatic" shock reflection if the problem terminates incorrectly after the shock is reflected by the program.)

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(Card No. 2 Continued)

Col 28-29	ICON(6)	N The boundary equation at which it is desired to begin the characteristic solution to automatically restart a reflected shock. This must be an upper solid wall equation (see Section 3.1.2)
Col 30	ICON(6)	0 Only the flowfield data generated after a shock is automatically reflected will be saved on the output tape. 1 The data generated before a shock is automatically reflected will be saved on the first file of the output tape and the flowfield data generated after the shock is reflected will be written on the second file of the flowfield tape. (This option requires the use of computer system routines which space past records on data tapes.)

NOTE: ICON(6) is the controlling flag for the "automatic" shock reflection. Cards 13, 14 and 15 are also required for "automatic" reflection.

Col 35	ICON(7)	0 Two-dimensional solution 1 Axisymmetric solution
Cols 37-38	ICON(8)	This option controls the type of output obtained after the problem has reached a free boundary equation. The same scheme is used in cols 37-38 as in 39 and 40. If blanks are used in Cols 37-38 then Cols 39 and 40 will control the printout for the entire run. (Ref. Section 3.1.2).
Col 39	ICON(8)	0 Full output 1 Limited output (Boundary, shock, input and P-M points)
Col 40	ICON(8)	1 One line output (R, X, M, THETA, S, Shock Angle) 2 Two lines, above plus (Mach Angle, P, Density, T, V) 3 Three lines, above plus (MWT, GAMMA, TO*, PO*, S*)
Cols 41-43	ICON(9)	No. of left-running points up to and including upstream shock point. Used when $ICON(2) \geq 20$ and shock crosses starting line. (See Section 3.1.2, p. 3-14.)
Cols 44, 45	ICON(9)	Number of regular start line points if $ICON(2) \geq 20$
Col 50	ICON(10)	0 Not presently used
Cols 51-55	ICON(11)	Case number (prints at top of each page)
Col 60	ICON(12)	0 Calculate shock wave 1 No rotation option

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(Card No. 2 Continued)

Col 65	ICON(13)	0 Do not use the viscous option to set up the start line 1 Use the viscous option to set up a start line at a nozzle exit plane. (See Card 12, Section 3.1.2 and Appendix)*
Cols 69-70	ICON(14)	N Number of Prandtl-Meyer rays to be used in expansions O Program will determine number of rays to be used.
Col 74	ISTOP	0 Single case is being run 1 Multiple cases are being run
Cols 75	ICON(15)	0 Mesh control is not desired 1 Mesh control is desired (Ref. Section 3.1.2 and Appendix)
Col 80	ICON(16)	0 No printout 1 Printout intermediate data**

* Entire start line must be a regular start line at the exit plane.

** This option causes intermediate calculations to be printed out during shock and pitot pressure calculations. This option was used during program check-out and is not generally required except for debugging purposes.

CARD NO. 3

Describes physical boundaries of the flow field. For use when ICON(4) and/or ICON(5) ≤ 100 .

Format: II, 3X, II,
5X, 6E10.6

Col 1	IWALL	1, Conic equation $R=A*(\text{SQRT}(B+C*X+D*X**2)+E)$ (See Section 3.1.2 pg. 3-17 for an example and description)
Col 1	IWALL	2, Polynomial equation $R=A*X**4 + B*X**3 + C*X**2 + D*X + E$
Col 1	IWALL	3, Free boundary equation $P=\text{PINF}*(1+E*X)*(1+\text{GAMMAINF}*(\text{MINF}*\text{SIN}*(\text{THETAB} - \text{THETAINF}))**2)$ (See Section 3.1.2 pg.3-17 for an example and description)
Col 1	IWALL	6, Free boundary equation of same form as IWALL=3, except oblique shock solution is used to generate plume boundary. Use number 6 for free stream approach flow in range of Mach 1.5 to 5.5.

NOTE: The problem uses air with a molecular weight of 28.966 for these oblique shock calculations.

Col 5	ITRANS	0 No discontinuity follows this equation
	ITRANS	1 Expansion corner follows this equation
	ITRANS	2 Compression corner follows this equation
Cols 11-20	WALLCO(I, 1, J)	A(If IWALL = 1 or 2), PINF (If IWALL=3) (Psfa)
21-30	WALLCO(I, 2, J)	B(If IWALL = 1 or 2), GAMMAINF (If IWALL=3)
31-40	WALLCO(I, 3, J)	C(If IWALL = 1 or 2), MINF (If IWALL=3)
41-50	WALLCO(I, 4, J)	D(If IWALL = 1 or 2), THETAINF (If IWALL=3)
51-60	WALLCO(I, 5, J)	E(If IWALL = 1 or 2), E(If IWALL=3)
61-70	XMAX	Maximum X value for which this equation applies.

NOTE: The coefficients of each equation are contained on a single card. As many cards, i.e., equations, as necessary to describe the boundaries are input. The units of physical dimensions affect only the thrust calculations in which units of feet are assumed. Upper boundary information is given first. Program assumes that starting line is bounded by solid walls and that the equations are ordered with XMAX monotonically increasing.

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CARD NO. 3A

Optional, physical flowfield boundary condition for use when ICON(4) and/or ICON(5) ≥ 1000 .

Format:	6E10.6	
Cols 1-10	RC	Radius of curvature of nozzle throat
11-20	RT	Radius of nozzle throat
21-30	THETA	Nozzle throat divergence angle
31-40	XO	Axial coordinate shift (Axial distance from the origin of the coordinate system to the throat)
Cols 1-10	XIN(I)	Each pair of XIN(I) and YIN(I) represents a discrete point for spline-fitting of the nozzle solid boundary. As many of these points as necessary can be input to a maximum of 100. Points must be input with XIN(I) monotonically increasing.
11-20	YIN(I)	
21-30	XIN(I+1)	
31-40	YIN(I+1)	
41-50	XIN(I+2)	
51-60	YIN(I+2)	

NOTE: The first point describing the wall must be downstream of the throat equation.

Cols 1-10	XIN(I+3) YIN(I+3) etc .	
Format:	11, 5X, 11, 5X, 6E10.6	
Col 1	IWALL	3 Free boundary equation
Col 5	ITRANS	0 No discontinuity follows this equation.
Col 11-20	WALLCO	PINF
21-30	"	GAMMAINF
31-40	"	MINF
41-50	"	THETAINF
51-60	"	E
61-70	"	XMAX

NOTE: Optional boundary description, Card Type 3A, is set up specifically for a rocket nozzle. The first card describes the nozzle throat, which is followed by cards containing sets of discrete points, three per card, describing the nozzle contour. The points will be automatically spline-fit to form equations for the contour. It is assumed that a free boundary equation follows the last nozzle point. Card types 3 and 3A may be mixed, i.e., the upper boundary may be described by type 3A while the lower boundary is described by type 3, or vice versa. Card type 3 and 3A may not be used simultaneously for a given boundary.

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CARD NO. 4

Gas Identification and Gas Property Input Control

Format: 4A6, 5X, A3,
6X, I2, 3X, I2

Cols 1-24 ALPHA

Gas name, identification for real gas properties on tape. May be any name when gas properties are input via cards.

Cols 30-32 UNITS

ENG English units are to be input (cards only)
MKS Metric units (cards or tape)

Cols 39-40 IOF

Number of O/F cuts, 1 min., 10 max.

Cols 44-45 IS

Number of entropy cuts (ignored for tape, 1 for ideal gas, 2 max for real gas via cards).

CARD NO. 5

O/F value of each table (must be input even if constant O/F case is run). O/F tables must be input with O/F values monotonically increasing.

Format: E10.6

Cols 1-10 OFRAT

CARD NO. 6

Entropy value and number of velocity cuts. (Not input if ICON(1) = 2, i.e., gas properties via tape; 0.0 if ideal.)

Format: E10.6, 8X, I2

Col 1-10 STAB

Entropy value

Col 19, 20 IVTAB

Number of Mach numbers for this entropy value 13 max, (1 if ideal gas)

CARD NO. 7

This card(s) gives the Mach number and associated gas properties at that Mach number and entropy.

Format: 5E10.6

Cols 1-10 TAB(I, J, K, 1)

Mach number

Cols 11-20 TAB(I, J, K, 2)

Gas constant (R) if UNITS = ENG, Molecular weight (MWT) if UNITS = MKS.

Cols 21-30 TAB(I, J, K, 3)

GAMMA

Cols 31-40 TAB(I, J, K, 4)

Temperature at this Mach number

Cols 41-50 TAB(I, J, K, 5)

Pressure at this Mach number

Units	MKS	ENG
Temperature	°K	°R
Pressure	Atmospheres	psfa
Gas Constant (R)	(Molecular Weight)	1545.2x 32.2/Mwt

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(Card 7 continued)

NOTE: If two O/F tables were input with 2 entropy tables and 10 velocity "cuts" for each entropy the cards would be arranged as follows:

Card 5
Card 6
Cards 7 (10 ea)
Card 6
Card 7 (10 ea)
Card 5
Card 6
Card 7 (10 ea)
Card 6
Card 7 (10 ea)

NOTE: Cards number 5, 6, and 7 are omitted if gas properties are input via tape.

CARD NO. 8

This card specifies the necessary information for the starting line. (If ICON(2) \neq 2, 12 or 22) (Ref. Section 3.1.2)

Format:	8E10.6	
Cols 1-10	CORLIP(1)	Axial coordinate of upper limit of start line.
Cols 11-20	CORLIP(2)	Axial coordinate of lower limit of start line.
Cols 21-30	CORLIP(3)	Mach number or A/A* for start line.
Cols 31-40	CORLIP(4)	Entropy level of start line.
Cols 41-50	STEP(5)	Area of nozzle throat (units consistent with boundary equations) (Must be input for thrust coefficient calculation). This must also be input if the start line is generated by conservation of mass.
Cols 51-60	CORLIP(5)	Constant O/F value
Cols 61-70	STEP(6)	Minimum ΔP for discontinuing shock calc. If zero is used the program assumes .001 (Ref. Section 3.1.2)

CARD NO. 9

These cards are used to read in a known starting line (ICON(2) = 2, 12 or 22). Omit when Card no. 8 is used. As many of these cards are input as specified by ICON(3) on the run control card. Used only if ICON(2) = 2, 12, or 22. (Ref. Section 3.1.2)

Format:	8E10.6	
Cols 1-10	PSI(K, 1)	Radial coordinate of this point
Cols 11-20	PSI(K, 2)	Axial coordinate of this point
Cols 21-30	PSI(K, 3)	Mach number of this point
Cols 31-40	PSI(K, 4)	Flow angle of this point
Cols 41-50	PSI(K, 5)	Entropy level of this point
Cols 51-60	PSI(K, 6)	Shock angle of downstream shock point.
Cols 51-60	STEP(5)	For last card only STEP(5) where STEP(5) is the area of nozzle throat (units consistent with boundary equations, must be input for thrust calculation).
Cols 61-70	STEP(6)	For last card only STEP(6) where STEP(6) is the minimum ΔP for discontinuing shock calculation.
Cols 71-80	PSI(K, 8)	Value of O/F at each starting line point.

NOTE: To use the variable O/F capability, supply a value of O/F for each input point. Option 2 for ICON(2), must be selected for starting line input. For constant O/F operation supply one O/F table and set O/F constant on card 8.

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CARD NO. 10

This card contains the necessary information to limit the calculations to those areas of interest. An unusual scheme is employed in order to make these limits efficient for the many problem orientations which are possible. Units should be consistent with those used on card 3. (Ref. Section 3.1.2)

Format: 8E10.6

Cols 1-10 CUTDAT(1)
 Cols 11-20 CUTDAT(2)
 Cols 21-30 CUTDAT(3)
 Cols 31-40 CUTDAT(4)

Radial coordinate defining upper cutoff.
 Axial coordinate defining upper cutoff.
 Angle cutoff line makes with horizontal.
 Radial coordinate defining downstream cutoff.

Cols 41-50 CUTDAT(5)

Axial coordinate defining downstream cutoff.

Cols 51-60 CUTDAT(6)
 Cols 61-70 STEP(3)

Angle cutoff line makes with horizontal.
 Point Insert Criteria. If the change in axial distance between two characteristic lines along the axis exceeds Step (3) a new characteristic point will be inserted. If nothing is input the program will use 10,000. Free stream temperature ($^{\circ}$ R). Use only if IWALL=6 on card 3.

Cols 71-80 TINF

CARD NO. 11

Mesh control parameters, controls mesh size by inserting or deleting points. Use this only if ICON(15) on Card 2 is greater than zero. (Ref. Section 3.1.2 and Appendix)

Format: 6E10.6

Cols 1-10 DIV(1)
 Cols 11-20 DIV(2)
 Cols 21-30 DIV(3)
 Cols 31-40 DIV(4)
 Cols 41-50 DIV(5)
 Cols 51-60 DIV(6)

Length control abs. Δl insert
 Length control abs. Δl delete
 Mach No. control abs. ΔM insert
 Mach No. control abs. ΔM delete
 Flow angle control abs. $\Delta \theta$ insert
 Flow angle control abs. $\Delta \theta$ delete

CARD NO. 12

This card contains the input information for the viscous boundary layer option. Use this card only if ICON(13) on Card 2 is greater than zero. (Ref. Section 3.1.2 and Appendix)

Format: I1, 2X, I2,
 5X, 2E10.6

Col 1 NPOWER

Reciprocal of the exponent of the velocity profile in the boundary layer

Cols 4, 5 NBLPTS

Number of boundary layer points specified

Cols 11-20 XL

A characteristic length (usually nozzle wall length)

Cols 21-30 CU

Conversion factor for mixed units of length.

Automatic Shock Reflection (Cards 13, 14, and 15)

If the automatic shock reflection option is used a namelist must be used to change some of the original input data. It is possible to change any of the ICON variables of Card 2, cutoff data of Card 10, mesh control criteria of Card 11 and point insert criteria of Card 10. The cutoff data must be changed to indicate a reflected or inverted case. Angle cutoff parameters of Card 10 are input in radians on the namelist.

CARD NO. 13 (For reflected shock cases only)

Col 2-7 \$INPT2 Control card for namelist

CARD NO. 14

Format: Free Field

Col 2-72 Changes to data consisting of for example:
 *Cutoff data array - CUTDAT(6)
 *Mesh control array - DIV(6)
 *Control array - ICON(16)
 *Point insert - STEP(3)

A typical example of the namelist card is:

CUTDAT(1) = 100., CUTDAT(2) = 0.0, CUTDAT(3) = 0.0
 CUTDAT(4) = -100., CUTDAT(5) = 100., CUTDAT(6) = 1.57
 DIV(1) = 40., ICON(6) = 1000

CARD NO. 15

Col 2-5 \$END End of data card.

* Cutoff data array is mandatory change to reset problem limits. All other namelist changes are optional.

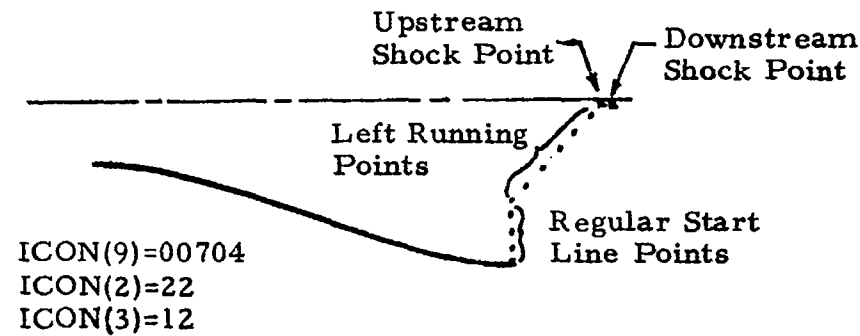
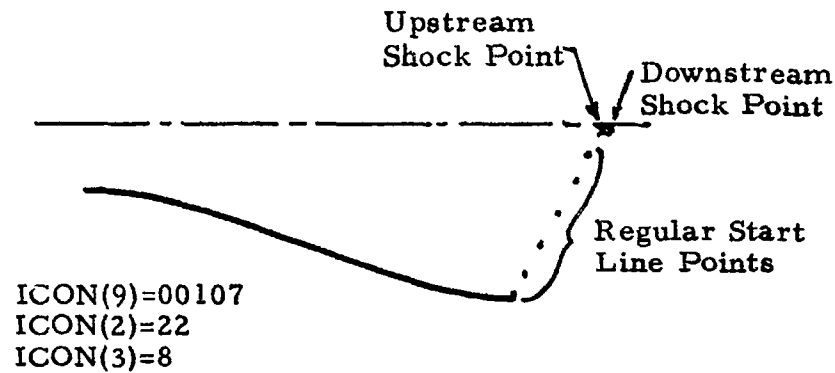
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3.1.2 Input FORTRAN Symbols

<u>Symbol</u>	<u>Description</u>	<u>Units (i appl)</u>
HEADER(I)	This array contains the problem description which is written at the top of every page of printed output. This header input with Card 1 of the input data.	N/A
ICON(1)	Used to tell the program if the gas properties are read in from cards (ICON(1) = 1) or read from tape 10 (A6)(ICON(1) = 2) which was generated by the NASA Lewis Thermochem Program and Tapgen program. After the gas properties have been written on the output tape ICON(1) is used by subroutines TABLE and FABLE for communication.	N/A
ICON(2)	ICON(2) is the type of starting line the program is to calculate or read in from cards. ICON(2) consists of 2 digits. The first digit is a 0, 1 or 2 for a normal start line, a right-running start line or a left-running start line respectively. The second digit is a 0, 1, 2 or 3 for a straight start line Mach No. given, source start line A/A* given, starting line input or starting line calculated by conservation of mass respectively. The second digit is used in subroutine PLUMIN for a computed go to statement which calculates or reads in the starting line depending on the type desired. The first digit is used in PHASE 1 to initialize the starting line into a usable array for beginning the method-of-characteristics solution.	N/A
ICON(3)	The total number of starting line points input or desired to be calculated by the program. Used as a reference for determining when the starting line points are used up.	N/A

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
ICON(4)	ICON(4) is a dual purpose input parameter. When it is not desired to input an upper boundary with points, ICON(4) is the number of upper boundary equations and ICON(4) is used to read in the desired number of upper boundary equations. When it is desired to curve-fit the upper boundary ICON(4) is 1000 plus the number of discrete points specifying the upper boundary plus 2 where 2 represents the nozzle throat equation and the free boundary equation. For the curve fit case ICON(4) is used to read in the information on the nozzle throat equation, the points representing the wall and the free boundary equation.	N/A
ICON(5)	Same as ICON(4) except ICON(5) applies to the lower boundary equations.	N/A
ICON(6)	This parameter supplies the program information necessary to automatically reflect a shock which intercepts the horizontal axis. ICON(6) is a four-digit number. The first digit is a 0 if it is not desired to have the start line punched and a 1 if it is desired that the start line be punched. The second and third digits are the number of the upper boundary equation which the program will use in restarting the problem. The program uses the last point on this upper boundary as the first point on the starting line. The fourth digit is either a one or a zero. If a one is used, an end of file mark is placed after the MOC data already on the output tape. If a zero is used, the MOC output created after the shock is reflected is written over the original output which was created before the reflection. This option requires system routines to space past end-of-file marks on flowfield tape which are not a part of the MOC program and must be a part of the individual computer system.	N/A

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
ICON(7)	The type of flowfield solution which is to be performed. A (0) for a two-dimensional solution and a (1) for an axisymmetric solution. ICON(7) is used in the mass flow calculations and in the axisymmetric term of the compatibility equation used for the solution of each characteristic point.	N/A
ICON(8)	ICON(8) indicates the type of printed output desired by the user. ICON(8) consists of two pairs of digits. The first pair controls the type of printout after the program begins using a free boundary equation for problem limits. The second pair indicates the type of output desired before the program begins using a free boundary equation or throughout the entire plume if nothing is input for the first two digits. The first digit of each pair controls the output at interior points on a characteristic line. If a zero is used the program will print out information at every characteristic point. If a one is used, printout will occur only at the boundary and shock points. The second digit is a 1, 2 or 3 for one, two or three line output at each point. (See output example.)	N/A
ICON(9)	ICON(9) is a dual purpose control for starting the characteristic solution of a reflected shock case. The first three digits are used for inputting the start line for a reflected shock case in which a left-running characteristic is crossed by the shock. These digits represent the total number of left-running points up to and including the upstream shock point. The last two digits are numbers of regular start line points. Two examples of this input are illustrated on the following page.	N/A



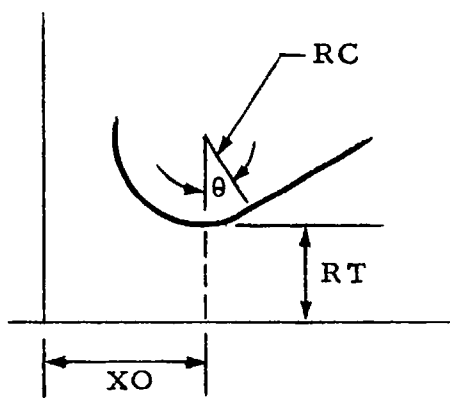
<u>Symbol</u>	<u>Description</u>	<u>Units</u>
ICON(10)	A flag which tells the program if a radiance tape is desired. A zero indicates no radiance tape and a 1, one tape, a 2, two tapes. The sub-routines for generating the radiance tapes are called through ICON(10) but the routines are presently dummied out.(See Capabilities section.)	N/A
ICON(11)	The case number for the problem under consideration. This number is printed out at the top of each page of output.	N/A
ICON(12)	A 0 allows the program to calculate a shock wave while a 1 will cause the program to skip the shock calculation. ICROSS is set equal to ICON(12) and ICROSS is used as a test for shock calculations.	N/A

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<u>Symbol</u>	<u>Description</u>	<u>Units</u>
ICON(13)	Flag which tells program to use a viscous calculation in setting up the starting line*. A zero does not read in viscous card and does not call subroutine VISCUS. A(1) reads in boundary layer information and calls subroutine VISCUS which calculates a boundary layer then merges the supersonic portion of the boundary layer into the starting line.	N/A
ICON(14)	ICON(14) is the number of Prandtl-Meyer rays to be used by the program in any expansions encountered in the solution. A zero will allow the program to calculate the number of rays. The program finds the limiting expansion angle then divides this angle into the number of rays to numerically integrate the Prandtl-Meyer expansion equation.	N/A
ICON(15)	ICON(15) is a two-digit number. The first digit is a flag which allows multiple cases to be run. When it is a 1 subroutine DRIVER reinitiates the program for the second case. A zero terminates the program after the first case has terminated. The second digit is used for reading in mesh control criteria. If it is a 1, the mesh control criteria are read in. If it is a zero, no mesh control is used in the solution.	N/A
ICON(16)	A flag which is set to a 1 will result in intermediate printout in the shock solution subroutines. There will be no intermediate printout if ICON(16) is a 0. This parameter is useful in program checkout.	N/A
IWALL	The type of boundary equation which is used in checking a characteristic point against problem boundaries. A 1 indicates a conic equation, a 2 a polynomial equation and a 3 a free boundary equation. (See following page for description and example.)	N/A

* At nozzle exit plane only.

A typical use of the conic equation is the throat of a nozzle. A sketch of a nozzle throat region shows the coefficients of circular throat.



- RC - radius of curvature of the circular arc of the throat
- RT - Throat radius
- XO - Axial distance from the origin of the coordinate system to the throat
- θ - Throat divergence angle corresponding to the maximum axial value for which the throat conic equation applies

The conic equation for this case would have the following form

$A = -1$ for an upper equation, $+1$ for a lower equation

(-1 for this case)

$$B = RC^2 - XO^2$$

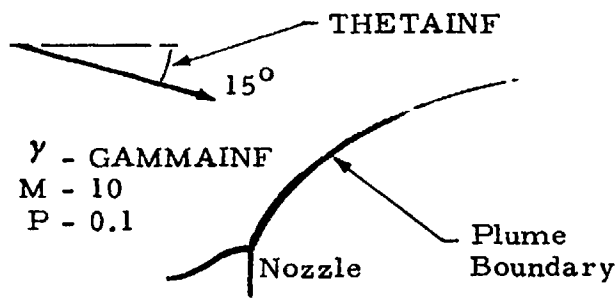
$$C = 2XO$$

$$D = -1$$

$$E = -(RC + RT)$$

$$X_{max} = RC \sin \theta + XO$$

An example of a free boundary is shown below.



The freestream approach flow is inclined at 15 deg to the plume with a gamma (γ) of 1.4, a Mach No. of 10., and a static pressure of 0.1 PSFA.

$P_{INF} = 0.1$ PSFA
 $E = 0$ (No pressure variation with axial distance)
 $GAMMA_{INF} = 1.4$
 $M_{INF} = 10$
 $THETA_{INF} = -15^\circ$

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<u>Symbol</u>	<u>Description</u>	<u>Units</u>
ITRANS	Indicates whether or not a discontinuity follows a particular boundary equation. ITRANS is used by the program in flagging calculations which will put a characteristic point at the exact location of the discontinuity (expansion or compression corner) so that a Prandtl-Meyer expansion or shock calculation may begin.	N/A
WALLCO(5)	The coefficients of the equations which describe the physical boundaries of the problems. These coefficients (A, B, C, D or E) and (PINF, GAMMAINF, MINF, THETINF or E) are used in either a conic or polynomial equation (A, B, C, D or E) or a free boundary equation (PINF, GAMMAINF, MINF, THETINF or E) depending on what was used for IWALL.	The radial and axial components of the equations should be consistent with units for the particular problem being run.
XMAX	XMAX is the maximum axial coordinate for which any one particular boundary equation is valid. XMAX is used by the program to test when the next boundary equation in the WALLCO(100, 6, 2) array should be used to check characteristic points against the physical boundaries of the problem. XMAX is stored in the 6th position of the WALLCO array.	Same as above.
RC	RC, RT, THETA, and XO are used when it is desired to curve fit an upper or lower wall equation. RC is the radius of curvature of the nozzle throat and is used in calculating the equation of the nozzle throat.	Consistent with the units in which XIN and YIN are input
RT	RT is the radius of the nozzle throat. RT is used in calculating the equation of the nozzle throat.	Consistent with the units in which XIN and YIN are input
THETA	The nozzle throat divergence angle. THETA is used to determine the maximum axial coordinate for which the nozzle throat equation will be applied.	Degrees

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<u>Symbol</u>	<u>Description</u>	<u>Units</u>
XO	If the nozzle throat is not at the origin then XO is the distance from the origin to the nozzle throat.	Consistent with the units in which XIN and YIN are input.
XIN	The axial coordinate of a discrete point which is to be used in spline fitting the nozzle solid boundary.	The units of XIN and YIN should be the same as the units the program uses in the solution.
YIN	The radial coordinate of a wall point associated with a XIN coordinate.	
ALPHA	The gas name identifying the real gas properties on tape. This name is compared with the names of gas cases appearing on a master gas tape. When the program encounters the same case the gas data is read from the tape and stored for use by the program. If gas properties are to be read in from cards the only limit on the name is that it satisfy the format. This name is also written out at the top of the pages which contain the gas data written out.	N/A
UNITS	Either ENG or MKS. ENG can be used for cards only while MKS can be used for either cards or tape. If the gas properties are in MKS units, subroutine GASRD changes the gas properties to ENG units.	N/A

ENG and MKS units are as follows:

	ENG	MKS
Temperature	$^{\circ}\text{R}$	$^{\circ}\text{K}$
Entropy	ft^2/sec^2	$\text{cal}/\text{gram}^{\circ}\text{K}$
Pressure	psfa	ATM
Gas constant	1545.5×32.174	
	MWT	MWT (molecular weight)

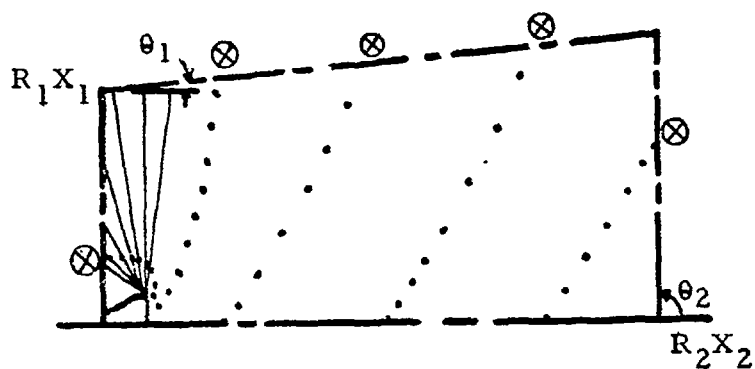
Note: These units are used only for inputting gas properties. Program uses ENG units internally.

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
IOF	The number of O/F ratio tables in the gas data. Used by the program for reading in gas properties from cards.	N/A
IS	The number of entropy cuts being considered for each O/F ratio table. Also used for setting limits on calculations and reading in gas properties from cards.	N/A
OFRAT	The O/F value for each O/F table. OFRAT is stored so that subroutine FABLE can locate the proper O/F tables to locate local gas properties in the flow field.	N/A
STAB	An entropy value associated with a table of velocity cuts at an O/F ratio. Used in table lookup for local gas properties.	ENG - $\frac{\text{ft}^2}{\text{sec}^2 \text{ } ^\circ\text{R}}$ MKS - $\frac{\text{cal}}{\text{gram } ^\circ\text{K}}$
IVTAB	The number of velocity cuts associated with a particular entropy cut.	N/A
TAB(I, J, K, ①)	The mach no. associated with a particular velocity cut and entropy for an O/F table.	N/A
TAB(I, J, K, ②)	The gas constant associated with the mach number and entropy for an O/F table.	$\frac{1545.4 \times 32.174}{\text{MWT}} - \text{Eng}$ MWT - MKS
TAB(I, J, K, ③)	GAMMA. The ratio of specific heats at a Mach no. and entropy for an O/F table.	N/A
TAB(I, J, K, ④)	The static temperature at the Mach no. and entropy for an O/F table.	$^\circ\text{R}$ - ENG $^\circ\text{K}$ - MKS
TAB(I, J, K, ⑤)	The static pressure at the Mach no. and entropy for an O/F table	PSFA - ENG ATM - MKS
CORLIP(2)	The axial coordinate of the upper limit of the start line. CORLIP(2) is read in when it is desired for the program to set up the start line. CORLIP(2) is used to find the radial coordinate and flow angle at this axial coordinate. The resulting point is the first point on the start line.	Consistant with boundary equation units.

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
CORLIP (6)	The axial coordinate of the lower limit of the start line. Used for locating the lower point on the start line.	Consistent with boundary equation units.
CORLIP(4)	The Mach no. or A/A* for the start line location. If the starting line is set up using A/A*, subroutine AOASTR is called with A/A* and the Mach no. for the starting line is determined. The starting line Mach no. is used in subroutine MASCON for determining a Mach no. distribution at the starting line.	N/A
CORLIP(5)	The entropy level of the starting line. Only used if the program sets up the starting line.	ft ² /sec ² _{OR}
CORLIP(8)	The area of the nozzle throat. This is used for thrust coefficient calculations.	Consistent with boundary equations.
CORLIP(9)	A constant O/F ratio across the starting line. This value is used only if the program is setting up the starting line. Note: The CORLIP values are used only if the program is to set up the starting line.	N/A
STEP(6)	The minimum percent change in pitot total pressure across a shock for discontinuing shock calculation. This is used to test shock strength. If the percent change from oblique shock theory is less than Step (6), then no iteration is performed by subroutine SHOCK, thereby keeping the shock strength the same. If nothing is read into the program, Step (6) is set to .001.	N/A
PSI(1, M)	For an input start line this is the radial coordinate for a particular starting line point.	Consistent with boundary equation.
PSI(2, M)	The axial coordinate of each start line point.	Consistent with boundary equations.
PSI(3, M)	The Mach no. at each start line point.	N/A
PSI(4, M)	The flow angle at each start line point.	Degrees
PSI(5, M)	The entropy level at each starting line point.	ft ² /sec ² _{OR}
PSI(6, M)	The shock angle downstream of the shock point on the start line. This value is input on first card only for a reflected shock case.	Degrees

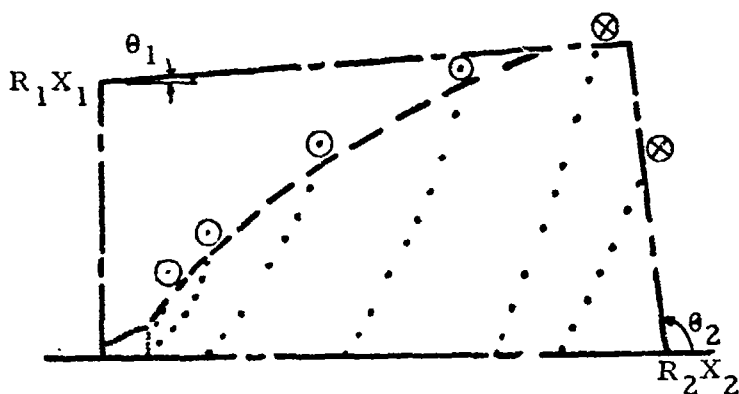
<u>Symbol</u>	<u>Description</u>	<u>Units</u>
PSI(8, M)	The value of the O/F ratio at each starting line point.	N/A
CUTDAT(1)	The radial coordinate defining upper cutoff of the characteristic solution.	Consistent with boundary equations.
CUTDAT(2)	The axial coordinate defining upper cutoff. If a characteristic point is calculated whose axial coordinate falls behind this coordinate the characteristic line is terminated and the next line started.	Consistent with boundary equations.
CUTDAT(3)	The angle the upper cutoff line makes with the horizontal. This line initiates from the point formed by CUTDAT(1) and CUTDAT(2). If a characteristic point is calculated which falls above this line the characteristic line is terminated and a new line begun.	Degrees
CUTDAT(4)	The radial coordinate defining downstream cutoff. If a characteristic point is calculated whose radial coordinate falls below this coordinate the line is terminated and a new characteristic line started.	Consistent with boundary equations
CUTDAT(5)	The axial coordinate defining downstream cutoff.	Consistent with boundary equations.
CUTDAT(6)	The angle the downstream cutoff line makes with the horizontal. The cutoff line initiates from the point formed by CUTDAT(4) and CUTDAT(5). If a characteristic point is calculated which falls beyond (and direct) this line the characteristic line is terminated and a new line begun. Note: The problem is terminated when a characteristic line is started beyond the limits set by CUTDAT's 1-6.	Degrees

Example of Cutoff Limits



① Lines Terminated due to Cutoff Limits Alone

- R_1 - CUTDAT(1)
- X_1 - CUTDAT(2)
- θ_1 - CUTDAT(3)
- R_2 - CUTDAT(4)
- X_2 - CUTDAT(5)
- θ_2 - CUTDAT(6)
- ⊗ - Line Terminated because of Cutoff Limits
- ⊙ - Line Terminated because of Free Boundary
- Characteristic Data Points along left-running characteristic lines



② Lines Terminated due to Cutoff Limits and Free (Pressure) Boundary

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<u>Symbol</u>	<u>Description</u>	<u>Units</u>
DIV(1)	The maximum change in absolute length (axial or radial) between either of the two base points and a new characteristic point. If the change in distance is greater than this maximum a new point is added by the program.	Consistent with boundary equations.
DIV(2)	The minimum change in absolute length (axial or radial) between either of the two base points and a new characteristic point. If any change in length is less than this minimum the new characteristic point will be deleted.	Consistent with boundary equations.
DIV(3)	The maximum change in Mach no. between either of the two base points and a newly calculated base point. If the change in Mach no. exceeds this maximum a new point will be inserted which will satisfy the criteria.	N/A
DIV(4)	The minimum change in Mach no. between either of the two base points and a newly calculated base point. If the change in Mach no. is not greater than this value the point will be deleted.	N/A
DIV(5)	The maximum change in flow angle between either of the two base points and the newly calculated point. If the change in flow angle is greater than the maximum a new point is added which will satisfy the criteria.	Degrees
DIV(6)	The minimum change in flow angle between either of the two base points and the new characteristic point. If the change in flow angle is less than this minimum then the point is deleted.	Degrees

Note: Mesh control explained in detail in Appendix.

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
NPOWER	The reciprocal of the exponent of the velocity profile in the boundary layer. This exponent is used only if the Reynolds number calculated for the case at the exit conditions at the wall indicates turbulent flow. If the flow is found to be laminar NPOWER is set to 2 by the program.	N/A
XL	A characteristic length which will be used to calculate the Reynolds no. and the boundary layer thickness. This value is usually taken as the nozzle wall length.	Ft
NBLTS	The number of starting line points which are desired in the boundary layer.	N/A
CU	A conversion factor for mixed units of length. This conversion factor should be such that XL(ft) will be converted into the same units used in the boundary equation. If inches are used in boundary equations, then CU will be 12. If boundary equations are in ft., CU is 1. CU is used in calculating the boundary layer thickness.	inches/ft or as required by boundary equation units.

NOTE: A detailed description of the boundary layer option is explained in the Appendix.

STEP(3)	Point insert criteria. Step(3) is the maximum change in axial distance between two consecutive characteristic lines on a lower wall. If this value is exceeded then a new left running characteristic line is started at the lower wall.	consistent with flow-field units
TINF	Free stream static temperature. This temperature is used for the oblique shock calculation of the plume free boundary when IWALL on card 3 is set to a 6.	°R

3.2 PROBLEMS COMMONLY ENCOUNTERED

This section is intended to aid the user in utilizing the program and avoiding some common problems. The comments on mesh control and starting line points are only initial guidelines. A "feeling" for the starting line points and mesh control criteria will result as the user becomes familiar with the operation of the program.

The following is a list of hints to the user:

- If an automatic restart is not desired when a shock intersects the axis, set ICON(6) to zero in Cols 28, 29 and 30 on Card 2. (Refer to Section 3.1.2 and the Appendix.)
- If it is desired to keep the type of printed output the same throughout the entire plume use only Cols. 39 and 40 of Card 2 (ICON(8)).
- For inputting a start line for a highly expanded plume the start line points should be more highly concentrated near the nozzle wall.
- When setting up a nozzle wall with discrete points the first spline fit point must not be a part of the nozzle throat equation (i.e., the first input point should be beyond the maximum axial coordinate for which the throat equation applies).
- In general, the mesh control criteria can be relaxed as the number of start line points increases.
- For highly expanded nozzles where a very large plume is to be generated an approximate mesh control criteria for the maximum Mach quadrilateral size is 20 exit diameters. Corresponding values for Mach number and flow angle criteria would be about 10 and 20° respectively.
- If problems in the solution are encountered due to characteristic lines diverging, decrease the maximum mesh control criteria so that more lines may be added.
- When the messages "negative velocities encountered" or "subsonic Mach number encountered," first check the input data. If no errors are noted in the input data decrease the mesh control criteria, or alter the number of start line points.

3.3 BASIC LIST OF SUBROUTINES, SIMPLE PROGRAM FLOWCHART AND COMMON BLOCK VARIABLES

- General Flowchart
- Lists of Subroutines according to function within the program
- Definition of all common block variables

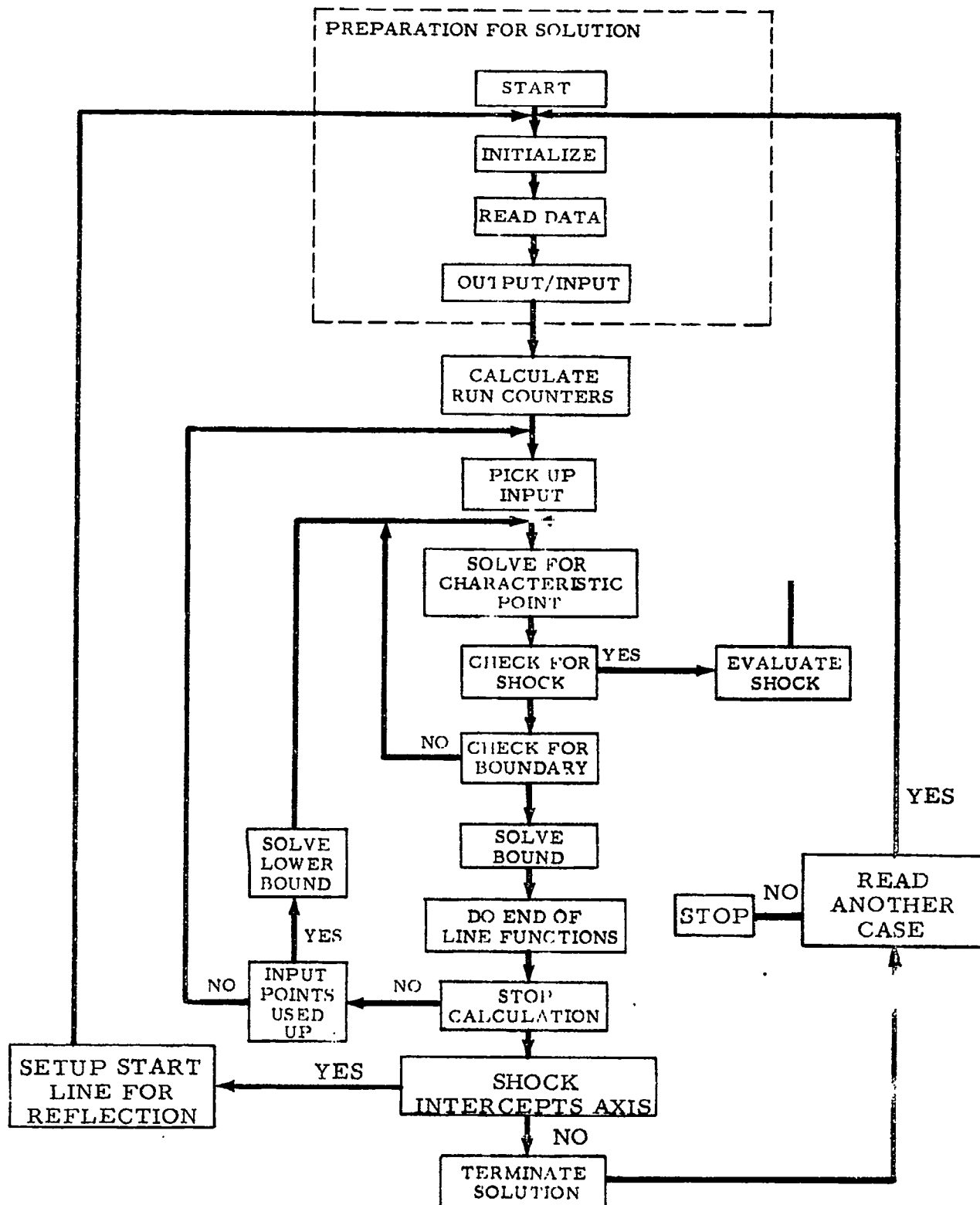


Fig. 3-1 - General Flow Chart

3.3.1 Program Routines

The following subsection contains a list of the routines according to their function performed within the program. Included are:

- General Flow Properties Routines
- Characteristic Solution Routines
- Shock Routines
- Logic Control
- Tape Manipulation Routines
- Start Line Setup Routines
- Problem Limit and Boundary Routines
- Input/Output Routines
- Utility Routines

GENERAL FLOW PROPERTIES
ROUTINES

<u>Routine</u>	<u>Function</u>
EMOFP	finds Mach number as a function of local static pressure and entropy.
EMOFV	finds Mach number as a function of velocity.
FABLE	finds local gas properties as a function of O/F ratio with the aid of (TABLE)
FNEWTN	finds Newtonian impact pressure at the plume boundary.
HYPER	calculates the balanced pressure at the intersection of a solid boundary and pressure boundary.
POFEM	finds static pressure as a function of Mach number and entropy.
PRANDT	finds the Prandtl-Meyer expansion angle for a given boundary angle and divides the angle into a series of expansion "rays". Then the flow properties are determined for each "ray".
RGMOFP	finds Mach number as a function of static pressure, entropy and O/F ratios.
RGVOFM	finds velocity as a function of Mach number, entropy and O/F ratio.
RHOFEM	finds density as a function of Mach number and entropy.
TABLE	finds local gas properties for an entropy and velocity within an O/F table. Uses tables of gas properties input to the program.
THETPM	performs a numerical integration to calculate properties through a Prandtl-Meyer expansion.
TOFEM	finds static temperature as a function of Mach number.
TOFV	finds static temperature as a function of velocity.
UOFEM	finds Mach angle as a function of Mach number.
UOFV	finds Mach angle as a function of velocity.
VOFEM	finds velocity as a function of Mach number.

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CHARACTERISTIC SOLUTION ROUTINES

<u>Routine</u>	<u>Function</u>
MOC SOL	provides all two-dimensional and axisymmetric methods of characteristic solutions.
MONO	determines if the characteristic point locations are monotonic along left or right running lines.
ROTERM	finds the geometrical factor used in the axisymmetric term of the compatibility equation and as an interpolation parameter.

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SHOCK ROUTINES

<u>Routine</u>	<u>Routine</u>
CONIC	solves for flow properties immediately downstream of a shock initiating from conic surface immersed in the flow.
DELTAF	computes the turning angle through an oblique shock knowing the shock angle and the upstream Mach no.
ENTROP	finds entropy rise across a shock as a function of shock angle and upstream Mach number.
ESHOCK	uses an iterative solution to perform equilibrium shock calculations.
OVEREX	finds the shock angle at the nozzle lip for over expanded flow.
SHOCK	iteratively adjusts the shock strength in order to satisfy the oblique shock relations and the flow field properties simultaneously.
TURN	solves for a shock wave which has a known turning angle.
WEAK	finds entropy and velocity downstream of the shock.

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LOGIC CONTROL

<u>Routine</u>	<u>Function</u>
DRIVER	provides highest order control for program execution. The initialization and logic subroutines are called from here.
KIKOFF	allows control to return to DRIVER if an error is encountered in the calculations.
PHASE1	provides the necessary logic to employ the proper calculations at the proper time in order to describe the entire characteristic mesh.
BLCKBX	provides controlling logic for automatic restart of a reflected shock case.

TAPE MANIPULATIONS ROUTINES

<u>Routine</u>	<u>Function</u>
GASRD	reads gas properties from cards and converts gas properties from MKS to English (ENG) units if necessary.
GASTAP	reads real gas properties from tape generated by the NASA Lewis Thermochemical Data program and writes data on output tape.
IDTAPE	writes gas properties read from cards on flow field tape.
JWBTSS	finds flow properties at each point along the starting line for the automatic restart of the reflected shock case.
OUTBIN	writes the calculated characteristic point data on the binary output tape.
READB	reads the position of the boundary points from the flow-field tape.
READF	reads one characteristic line from the flowfield tape and saves flow properties at each point on the line.
TAPMOV	moves the flowfield tape through the gas properties to the beginning of the flowfield information.

START LINE SETUP ROUTINES

<u>Routine</u>	<u>Function</u>
AOASTR	finds the Mach no. corresponding to a given area ratio.
LIPIN	calculates information for starting line points setup by the program.
MASCON	calculates Mach no. distribution at any area downstream of the nozzle throat while conserving total mass flow.
SETUP	locates and distributes start line points for the automatic restart of the reflected shock case.
VISCUS	calculates the boundary layer thickness at the nozzle exit and adjusts the starting line to consider the boundary layer.
WOFA	finds weight flow per unit area as a function of Mach number.

PROBLEM LIMITS & BCUNDARY ROUTINES

<u>Routine</u>	<u>Function</u>
BOUND	finds the radial coordinate and flow angle for a given axial coordinate on an upper or lower solid boundary.
ITERM	tests each characteristic point to determine if it lies within problem limits.
LIMITS	determines which boundary equation to use in checking on problem limits.
SOLVE	finds the coefficients of the nozzle wall cubic equation described by points input to the program.
SWITCH	transfers upper and lower boundary equations for automatic reflected shock restart case.
THROAT	computes the nozzle throat equation for a nozzle wall described by discrete points.

INPUT/OUTPUT ROUTINES

<u>Routine</u>	<u>Function</u>
ERRORS	writes out various messages for errors which may occur during program execution.
OUT	writes the calculated data at characteristic points along with the title and heading.
PAGE	page ejects and writes header comments and page number on each page of printout.
PLUMIN	reads in the input data necessary to perform the method of characteristics solution.
PLMOUT	prints data read by (PLUMIN).

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MISCELLANEOUS ROUTINES

<u>Routine</u>	<u>Function</u>
ICHECK	this routine determines whether a characteristic point is added or deleted depending on the mesh control criteria.
INITP	initializes values for various control parameters.
INRSCT	find intersection of two straight lines.
ITSUB	controls the iteration for any set of equations that are expressed as a function of one variable.
MASSCK	keeps a running check on the mass flow under each point along a characteristic line.
PRANDT	finds the Prandtl-Meyer expansion angle for a given boundary angle and divides.
SAVER	saves data at nozzle lip.
THRUST	computes the vacuum thrust produced by a two-dimensional or axisymmetric nozzle.

3.3.2 Common Variables

This subsection contains a list of the common block variables along with a description of each variable and the routines using each common block.

<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/CARDT/	ICARD	If ICARD is a 1 subroutine IDTAPE will write gas data on output tape. If ICARD is not a one subroutine GASTAP will read the master gas tape or write the gas data on the output tape. (ICARD is used in automatic shock reflection.)	BLCKBX GASRD DRIVER
/CONTRL/	IRUN(10)	Control flags used by the program during the plume generation.	DRIVER ESHOCK FABLE GASRD GASTAP IDTAPE INITP KIKOFF LIMITS LIPIN MASCON MASSCK MOCSOL OUT PAGE PHASE1 PLMOUT PLUMIN PRANDT RGMOPF RGVOFM SHOCK TABLE THRUST TURN VISCUS
	ICON(16)	Input controls used by the program.	
/CRITER/	CONVRG(10)	Array of convergence criteria.	DRIVER INITP MOCSOL PRANDT SHOCK TURN
	ITLIM(10)	Array of iteration limits.	

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<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/CUTFO/	CUTDAT(6)	cutoff limitations (problem limits)	DRIVER ITERM PLMOUT PLUMIN
/DATAR/	PHO(8, 100, 2)	Local gas properties array for all characteristic points on the line the program is calculating and the previous characteristic line.	BOUND DRIVER FABLE FNEWTN GASRD GASTAP HYPER ICHECK IDTAP INITP
	PHO(100, 2)	Type of characteristic point for each point on the new characteristic line and the previous one.	ITERM LIMITS MASSCK MOCOSOL MONO OUT
	APHO(100, 2)	Array which stores the Mach no. for each point on the new characteristic line and the previous one.	OUTBIN OVEREX PHASE1 PLMOUT PLUMIN PRANDT RGMOFP RGVOFM SHOCK SOLVE TABLE THRUST
	OFRAT(10)	O/F ratio for each O/F table.	
	STAB(10, 2)	Entropy values for each O/F ratio table.	
	IVTAB(10, 2)	Number of velocity cuts in each entropy table for each O/F ratio.	
	TAB(10, 2, 13, 5)	Local gas properties for each velocity cut in each entropy table for each O/F ratio.	
	WALLCO(100, 6, 2)	Wall coefficients and maximum X for each upper and lower wall equation.	
	IWALL(100, 2)	Type of each upper and lower wall equation.	
	ITRANS(100, 2)	Contains flag for each wall equation telling program whether an expansion corner, compression corner or no discontinuity follows the equation.	
	IEQNOW(2)	Counter on the upper and lower boundary equations.	

<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/DEL/	IDEL	Flag used for printing out which of the mesh control criteria a point has not satisfied.	
	DECRE	The distance, Mach no. or flow angle for the point which did not satisfy the mesh control criteria.	
/DIVCRI/	DIV(6)	Mesh control parameters which control mesh size by inserting or deleting points.	DRIVER ICHECK PLMOUT PLUMIN
/FAB/	T	Local temperature at point of interest.	FABLE TABLE
	P	Local pressure at point of interest	
	SP	Local entropy at point of interest	
/FLAG/	IFLAG	Determines if gas properties have been read into program; 1 - not read in - 2 - have been read in.	BLCKBX JWBTS
	JFLAG	Indicates if last point was in plume; 2 - last point in plume; 1 - last point not in plume.	
	KFLAG	Indicates if present point is in plume; 0 - not in plume; 1 - is in plume.	
/FORCE/	FORCEX	Total axial force on nozzle up to the last calculated characteristic line.	DRIVER MASSCK THRUST
	FORCEY	Total radial force on nozzle up to the last calculated characteristic line.	
	TORQZ	Total moment about the origin due to FORCEX and FORCEY.	
	EMASS	Total mass flow passing through the nozzle.	

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<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/GASCON/	R GAMMA TO PO ASTER	Local gas constant in plume Local isentropic exponent in plume. Total temperature. Total pressure. Flag which indicates whether gas properties are in table or not.	DELTAF DRIVER EMOFP EMOFV ENTROP ESHOCK FABLE GASRD MOCSOL OUT PHASE1 PLMOUT PLUMIN POFEM PRANDT RGMOPF RHOFEM SHOCK TABLE THETPM TOFEM TOFV VISCUS VOFEM WEAK WOFA
/HEAD/	HEADER(36)	Array containing the title of the MOC run.	DRIVER GASTAP IDTAP INITP OUT PAGE PI MOUT PLUMIN
/INPUT/	PSI(8,100)	Local gas properties array for each point on the starting line.	DRIVER LIPIN MASSCK PHASE1 PLMOUT PLUMIN THRUST VISCUS

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<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/IRECD/	IREC	A counter on the number of files written on the binary output tape.	DRIVER TAPMOV
	IFILE	Flag which tells the program where to begin writing on the binary output tape.	
/IRFEC/	IGORN	Flag which causes a message to be written out when the shock intersects the axis.	DRIVER SHOCK
/ITAPE/	ISTARO(50,3)	Contains the point number of the beginning of a new characteristic line which has been added due to mesh control. Also contains the point numbers of the two points used to generate the new point.	PHASE1 OUTBIN
	IREST	The line number identifying a characteristic which has been added due to mesh control.	
/POINTS/	XIN(100,2)	Axial location of points input to describe the upper or lower nozzle wall points.	PLUMIN SOLVE THROAT
	YIN(100,2)	Radial location of points input to describe the upper or lower nozzle wall points.	
	RC	Radius of curvature of the nozzle throat.	
	RT	Radius of nozzle throat.	
	THETA	Nozzle throat divergence angle.	
/QUIT/	XO	Axial coordinate shift.	DRIVER PLUMIN
	ISTOP	0 - one case is to be run. 1 - more than one case is to be run.	
/SHCKPT/	PMX(8)	Array which contains flow properties at the nozzle lip point or last calculated nozzle wall point (used for automatic shock reflections).	BLCKBX SAVER DRIVER

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<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/STEP/	STEP(10)	Array containing floating point information used as controls by the program.	DRIVER HYPER INITP MASSCK PHASE1 PLUMIN PRANDT THETPM THRUST
/TAPEFO/	ALPHA(4)	Identification of propellant case.	DRIVER FABLE GASRD
	IOF	Number of O/F ratio tables.	GASTAP
	IS	Number of entropy cuts for each O/F ratio table.	IDTAP PLMOUT RGMOPF RGVOFM
/UNITSS/	UNITS	The type of units the gas properties were read in as.	DRIVER GASRD
	ENG	Gas properties are in English units.	
	EMKS	Gas properties are in MKS units.	
/WHICH/	KAY	The line on which the shock wave has intersected the axis.	BLCKBX DRIVER PLUMIN PHASE1
	IWHARE	The boundary equation at which shock restart calculations are to begin.	
	ILINE	The type of printed output desired when the program begins using a free boundary equation for problem units.	
/WTSVAV/	WTSVAV(100)	Total mass flow passing under each point on a characteristic line.	MASSCK OUTBIN
/XSICOM/	XSI(10, 2, 13, 2)	Weighing factors for interpolating between velocity cuts over pressure and temperature.	

<u>Common Name</u>	<u>Variables</u>	<u>Definition</u>	<u>Routines Using</u>
/FINITE/	IFREE	A flag which is used to determine whether a free boundary is to be calculated using oblique shock theory.	ESHOCK FABLE FNEWTON PHASE1 TURN
	TINF	Freestream static temperature	
	OF	Not presently used	

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3.4 DESCRIPTION AND FLOW CHARTS OF INDIVIDUAL SUBROUTINES

FUNCTION NAME: AOASTR

DESCRIPTION

This function finds the Mach number corresponding to a given area ratio by one-dimensional theory. Real gas effects are considered in this calculation.

CALLING SEQUENCE

EM = AOASTR (OF, S, AOA)

where (EM) is the Mach number which exists, one dimensionally, at an area ratio of (AOA), an entropy (S), and at an O/F ratio (OF).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON-None

ERRORS

FABLE

ITSUB

RGVOFM

WOFA

METHOD OF SOLUTION

The weight flow per unit area at Mach one is evaluated. An initial guess for the desired Mach number is made and ITSUB is initialized. An iterative solution of the equation $FOFEM = AOA - WOFA1/WOFA(EM)$, driving FOFEM to zero, is performed with the aid of ITSUB.

SUBROUTINE NAME: BLCKBX

DESCRIPTION

This routine contains the controlling logic for automatically restarting the method of characteristics solution for a reflected shock case.

CALLING SEQUENCE

Call BLCKBX

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CARDT/	PLMOUT
COMMON/DIVCRI/	IDTAPE
COMMON/CUTFO/	GASTAP
COMMON/STEP/	TAPMOV
COMMON/INPUT/	FABLE
COMMON/FLAG/	EMOFV
COMMON/SHCKPT/	SETUP
COMMON/DATAR/	JWBTSS
COMMON/CONTRL/	SWITCH
COMMON/WHICH/	

METHOD OF SOLUTION

Not applicable.

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SUBROUTINE NAME: BOUND

DESCRIPTION

This subroutine finds the radial coordinate and flow angle (radians) for a given axial coordinate on an upper or lower solid boundary.

CALLING SEQUENCE

CALL BOUND (R, X, THETA, ITYPE)

where (R) is the radial coordinate, (X) is the known axial coordinate, THETA is the wall angle and ITYPE indicates whether upper or lower boundary equations are to be used.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/

UTILITY - None

METHOD OF SOLUTION

The block common region DATAR contains boundary equations necessary to evaluate R, THETA. Two types of equations are used;

$$r = a \left[\sqrt{b + cx + dx^2} + e \right] \quad \text{CONIC TYPE 1}$$

and

$$r = ax^4 + bx^3 + cx^2 + dx + e \quad \text{POLYNOMIAL TYPE 2}$$

The input fixed point variable ITYPE has a one or a two in the units position which selects the upper (2) or lower (1) coefficients and control information. IEQNOW contains the number of the equation to be used.

SUBROUTINE NAME: CONE

DESCRIPTION

This subroutine solves for the shock wave downstream properties formed at a right circular cone immersed axisymmetric supersonic flow.

CALLING SEQUENCE

Call CONE (OF, SU, QU, ALPHA, SD, QD, EPS)

where the input properties are (OF, SU, QU) the upstream O/F ratio, entropy, and velocity and (ALPHA) is the turning angle. The subroutine returns with (SD, QD) the downstream entropy and velocity and (EPS) the shock angle.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON - None
FABLE
TOFV
ESHOCK
EMOFV
ITSUB
ERRORS

METHOD OF SOLUTION

The oblique shock relations and characteristic relations are solved in an iterative manner to obtain the downstream flow properties.

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FUNCTION NAME: DELTAF

DESCRIPTION

This function computes the turning angle through an oblique shock wave knowing the shock angle and the upstream Mach number.

CALLING SEQUENCE

DELTA = DELTAF (EPS, EM)

where (DELTA) the turning angle is found from the shock angle (EPS) and the upstream Mach number (EM). NOTE: The appropriate values of gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CASCON/

UTILITY - None

METHOD OF SOLUTION

The oblique shock relations are solved for the turning angle using the relations;

$$\delta = \epsilon - \tan^{-1} \left\{ \tan \epsilon \left(\frac{1}{M^2 \sin^2 \epsilon} + \frac{\gamma - 1}{2} \right) \left(\frac{2}{\gamma + 1} \right) \right\}$$

SUBROUTINE NAME: DRIVERDESCRIPTION

Driver provides the highest order control for program execution. Initialization and logic subroutines are called from here. Most all the common storage needed in the remainder of the program is specified here.

CALLING SEQUENCE

CALL DRIVER (K)

where (K) is a control constant indicating whether or not errors exist in the execution of the program. (K=1 for a detected error, K=0 for no errors.)

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTROL/	COMMON/QUIT/
COMMON/CRITER/	COMMON/XSICOM/
COMMON/CUTFO/	COMMON/CARDT/
COMMON/DATAR/	COMMON/FLAG/
COMMON/DIVCRI/	COMMON/SHCKPT/
COMMON/FORCE/	COMMON/IRECD/
COMMON/GASCON/	COMMON/IRFEC/
COMMON/HEAD/	COMMON/UNITSS/
COMMON/INPUT/	INITP
COMMON/STEP/	PLUMIN
COMMON/TAPEFO/	PHASE 1
	BLCKBX

METHOD OF SOLUTION

Not applicable for this subroutine.

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FUNCTION NAME: EMOFP

DESCRIPTION

This routine computes the local Mach number as a function of local pressure (static) and the local entropy value.

CALLING SEQUENCE

$$EM = EMOFP (P, S)$$

where (EM) is the resultant Mach number found from the pressure (P) and entropy (S). NOTE: The appropriate values of the gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

UTILITY - None

METHOD OF SOLUTION

Perfect gas relationships (thermally perfect) are used to find the Mach number.

$$M = \sqrt{\left[\left(\frac{p_o e^{-S/R}}{P} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \frac{\gamma}{\gamma-1}}$$

FUNCTION NAME: EMOFV

DESCRIPTION

This routine finds Mach number as a function of velocity.

CALLING SEQUENCE

$$EM = EMOFV(V)$$

where (EM) is the local Mach number which is found as a function of (V) the local velocity. NOTE: The appropriate values of the gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/
TOFV

METHOD OF SOLUTION

Thermally perfect gas relationships are used to find the Mach number.

$$M = \sqrt{\left(\frac{T_o}{T} - 1\right) \left(\frac{2}{\gamma - 1}\right)}$$

FUNCTION NAME: ENTROP

DESCRIPTION

This routine utilizes the oblique shock relations to find the entropy rise across a shock as a function of the shock angle and the upstream Mach number.

CALLING SEQUENCE

SD = ENTROP (EPS, EMU)

where (SD) is the entropy rise across the shock and is a function of the shock angle (EPS) and the upstream Mach number (EMU). NOTE: The appropriate values of the gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

UTILITY - None

METHOD OF SOLUTION

The oblique shock relations are employed to find the entropy rise across the shock.

$$ds = \frac{R}{\gamma - 1} \left\{ \ln \left[\frac{(2\gamma M^2 \sin^2 \epsilon - (\gamma - 1))}{\gamma + 1} \right] + \gamma \ln \left[\frac{\tan(\epsilon - \delta)}{\tan \epsilon} \right] \right\}$$

SUBROUTINE NAME: ERRORS

DESCRIPTION

This subroutine contains print messages for various errors which may occur. This is an open ended routine in that it can easily be extended to handle more print messages.

CALLING SEQUENCE

CALL ERRORS (I)

where (I) selects the message to be printed.

UTILITY ROUTINES AND COMMON REFERENCES

None

METHOD OF SOLUTION

Not applicable.

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SUBROUTINE NAME: ESHOCK

DESCRIPTION

This subroutine employs an iterative solution to perform the equilibrium shock calculations for a real or ideal gas. The real and ideal gas calculations are similar, the difference being that an ideal gas case converges on the first iteration.

CALLING SEQUENCE

CALL ESHOCK (OF, S1, V1, EP, DELTA, S2, V2)

where the input properties are (OF) the upstream O/F ratio, (S1, V1) the upstream entropy and velocity and (EP) the shock angle. The subroutine returns with (DELTA), the turning angle and (S2, V2), the downstream entropy and velocity.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	POFEM
COMMON/GASCON/	DELTA
COMMON/FINITE/	ENTROP
EMOFV	RHOFEM
FABLE	WEAK

METHOD OF SOLUTION

The continuity equation coupled with the equations for conservation of normal and tangential momentum are solved in an iterative manner utilizing thermochemical property data to satisfy the conservation of energy. This set of 4 equations is expressed in terms of the 4 unknown quantities:

- ϵ - shock angle
- δ - turning angle
- S_2 - entropy downstream of shock
- V_2 - velocity downstream of shock

SUBROUTINE NAME: FABLE

DESCRIPTION

This subroutine utilizes real or ideal gas information obtained from the flowfield tape and a local O/F ratio to call subroutine TABLE to calculate thermodynamic gas properties locally in the flow.

CALLING SEQUENCE

CALL FABLE (OF,SS,V)

where (OF) is the local O/F ratio, (SS) is the local entropy and (V) is the local velocity.

UTILITY ROUTINES AND COMMON BLOCKS

COMMON/GASCON/
COMMON/DATAR/
COMMON/FAB/
COMMON/CONTROL/
COMMON/FINITE/
TABLE

METHOD OF SOLUTION

The routine is entered with the local O/F ratio (OF), entropy (SS), and velocity (V). The local ratio is used to determine which set of thermodynamic tables that subroutine TABLE should use to perform table lookup of the local thermodynamic gas properties. Subroutine FABLE then uses the local thermodynamic gas properties obtained from TABLE to perform an interpolation between the O/F tables based on the local O/F ratio.

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FUNCTION NAME: FNEWTN

DESCRIPTION

This function solves for the Newtonian impact pressure along the plume boundary. The calculation is applicable for hypersonic free stream velocities or quiescent conditions (i.e., $M_\infty = 0$). There is also an option whereby impact pressure at a free boundary is solved using oblique shock theory.

CALLING SEQUENCE

$$P_{IM} = \text{FNEWTN}(\text{THETA3}, X, \text{ITYPE1})$$

where (P_{IM}) is the hypersonic Newtonian impact pressure at the plume boundary, (THETA3) is the local flow angle at the boundary, (X) is the axial coordinate of the boundary point, and (ITYPE1) designates upper or lower boundary. (1 - lower, 2 - upper)

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/
COMMON/CONTROL/
COMMON/FINITE
TURN POFEM VOFEM
JOFEM EMOFV

METHOD OF SOLUTION

The block common region - WALLCO contains the necessary information to evaluate the free stream gas properties at the plume boundary point. The impact pressure is then calculated using the following equation

$$P = P_\infty (1 + eX) \left[1 + \gamma_\infty M_\infty^2 \sin^2(\theta_B - \theta_\infty) \right]$$

If the oblique shock option is used the free stream gas properties and impact pressure are calculated using subroutine TURN.

SUBROUTINE NAME: GASRDDESCRIPTION:

This subroutine reads in the gas properties. These properties may be real or ideal and read in via cards or tape. The routine also converts input gas properties from MKS units to English (ENG) units if necessary.

CALLING SEQUENCE

CALL GASRD

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/XSICOM/
COMMON/CONTRL/
COMMON/DATAR/
COMMON/GASCON/
COMMON/TAPEFO/
COMMON/UNITSS/
COMMON/CARDT/
GASTAP
IDTAPE

METHOD OF SOLUTION

The gas name (ALPHA(I)), type units, number of O/F tables, and number of entropy cuts are read in from an input card. If the gas properties are on cards, this subroutine reads the cards. If the gas properties are on tape, control of the reading of properties is given to GASTAP. In either case, the properties are converted from MKS to English (ENG) units by this subroutine if necessary.

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SUBROUTINE NAME: GASTAP

DESCRIPTION

GASTAP retrieves the real gas properties generated by the NASA LEWIS THERMOCHEMICAL DATA program and provides instructions for writing this data on the MOC flow field tape.

CALLING SEQUENCE

CALL GASTAP

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/DATAR/
COMMON/HEAD/
COMMON/TAPEFO/
ERRORS

METHOD OF SOLUTION

The gas name, (ALPHA(I)), specified on the input data is compared with available cases on the thermochemical data tape until a match is found. This particular case is then read, stored core in and written on the MOC flow field tape.

SUBROUTINE NAME: HYPER

DESCRIPTION

This subroutine calculates the balanced pressure at a corner point (i. e., at the intersection of a solid boundary and the pressure boundary). The pressure balance is determined for either the over or under expanded case with impact or ambient freestream pressure.

CALLING SEQUENCE

CALL HYPER (PB, I, K, ITYPE)

where (PB) is the boundary pressure, (I, K) locates the boundary point, and (ITYPE) indicates if upper or lower boundary is involved.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/
COMMON/STEP/PC/
FABLE
POFEM
EMOFV
FNEWTN
OVEREX
ITSUB
THETPM
ERRORS

METHOD OF SOLUTION

The boundary pressure (may be impact or ambient) is compared to static pressure of the corner point. Depending on whether the comparison indicates the flow is over or under expanded, a branch is made to (OVEREX) or (THETPM). In either of these routines an iterative process balances the boundary pressure with the flow field pressure at the boundary.

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SUBROUTINE NAME: ICHECK

DESCRIPTION

This function checks on the absolute difference in distance, Mach no., and flow angle between the new point and both the right and left running base points. This check determines if a point is added, deleted, or left in as calculated.

CALLING SEQUENCE:

IDO = ICHECK (I, K, I1, J, J2, K)

where (I, K), (I1, J), (I2, K) designate the new characteristic point, the right running base point, and the left running base point, respectively.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/
COMMON/DIVCRI/
FABLE
EMOFV
VOFEM

METHOD OF SOLUTION

Not applicable.

SUBROUTINE NAME: IDTAPE

DESCRIPTION

This subroutine writes the gas properties which were input via cards on the flow field program tape. The format used to write them on tape is compatible with that used for real gas.

CALLING SEQUENCE

CALL IDTAPE (UNITS)

where (UNITS) indicates whether the gas properties are being read in with English (ENG) or MKS units.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/
COMMON/TAPEFO/
COMMON/CONTRL/
COMMON/HEAD/
UTILITY - None

METHOD OF SOLUTION

Gas property data is read in from cards. If not already in MKS units, the data is converted. This converted data is then written on the flow field tape (tape 13).

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SUBROUTINE NAME: INITP

DESCRIPTION

This subroutine initializes the values of various control parameters, thereby providing for proper operation of the program. These initial values include:

1. the counter for the upper and lower boundary equations,
2. the counter for the first characteristic line,
3. the initial number of degrees per Prandtl-Meyer ray,
4. convergence criteria,
5. maximum number of iterations.

CALLING SEQUENCE

CALL INITP

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/CRITER/
COMMON/DATAR/
COMMON/HEAD/
COMMON/STEP/PC/
UTILITY - None

METHOD OF SOLUTION

Not applicable.

SUBROUTINE NAME: INRSCTDESCRIPTION

This subroutine finds the intersection of two straight lines.

CALLING SEQUENCE

CALL INRSCT (R1, X1, BETA1, R2, X2, BETA2, R3, X3)

where (R1, X1, BETA1) and (R2, X2, BETA2) define the equations of the two straight lines which intersect at (R3, X3).

UTILITY ROUTINES AND COMMON REFERENCES

None

METHOD OF SOLUTION

The equations of the straight lines are written

$$r = \tan \beta_1 (x - x_1) + r_1$$

and

$$x = \cot \beta_2 (r - r_2) + x_2$$

These equations are solved for x but a test on the slopes is made to prevent indeterminate forms. If an indeterminate form is possible, the points are mapped one onto another, thus precluding the possibility of indeterminacy except when the lines are parallel.

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FUNCTION NAME: ITERM

DESCRIPTION

ITERM tests each characteristic point to determine if it is within the predefined problem limits. If the point falls outside the limits, the present characteristic line is terminated. Control is then returned to PHASE1 for initiation of a new line.

CALLING SEQUENCE

FUNCTION = ITERM (IP, K)

where (IP) identifies the characteristic point on the new (K) line.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CUTFO/

COMMON/DATAR/

UTILITY - None

METHOD OF SOLUTION

The angular orientation of a line drawn from the upper or lower cutoff coordinates to the characteristic point is determined. Comparing this angle to the angle of the upper or lower cutoff line determines if the point is inside or outside the problem limits.

SUBROUTINE NAME: ITSUB

DESCRIPTION

This subroutine controls the iterative solution of any set of equations which can ultimately be expressed as a function of one variable. The routine can also be used to control an integration loop.

CALLING SEQUENCE

CALL ITSUB (FOFX, X, SAVE, CONV, NTIMES)

(FOFX) - function of X which is driven to zero

(X) - variable which is iteratively solved for

(SAVE) - program control, i.e., SAVE(1) is control counter,
SAVE(2) is X increment

(CONV) - convergence criteria

(NTIMES) - maximum number of iterations

UTILITY ROUTINES AND COMMON REFERENCES

None

METHOD OF SOLUTION

ITSUB modifies (X) in the proper direction by the decrement value (SAVE(2)) until the root has been bracketed. The method of false position is then used to modify X until the solution is reached. Immediately after entering ITSUB each time, the function is inspected for convergence. If the function has converged, a program control is set, and computer control is transferred to the calling routine.

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SUBROUTINE NAME: JWB TSS

DESCRIPTION

This subroutine performs all the flow field tape search operations for determining flowfield properties at each start line point for the automatic re-start of reflected shock. The routine is entered with the coordinates of a point on the start line, and a linear interpolation within the characteristics mesh produces flow field data at the desired point.

CALLING SEQUENCE

CALL JWB TSS (POINT)

where

Point (1) = radial or vertical coordinate of desired point

Point (2) = axial coordinate of desired point

Point (3) = Mach number at desired point

Point (4) = flow angle at desired point

Point (5) = entropy level of flow at desired point

Point (7) = velocity at desired point

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DUMPCO/

COMMON/FLAG/

READB

READF

TAPMOV

METHOD OF SOLUTION

The main function of the routine is to locate the start line point within the flow field or outside of its boundaries. If the start line point is found to be within the flow field, then flow field data is obtained at the location. This search operation is outlined in a series of steps performed by JWB TSS.

1. The routine first reads in the flow field boundary points and determines if it is possible for the start line point to be inside the flow field. If this test is negative, a flag is set accordingly and control is returned to the calling routine BLCKBX.

If the test is positive, step 2 is taken.

2. Characteristic lines are read in (one at a time) and retained in storage. As the lines are being read, each characteristic point is checked in an effort to bracket the body point. The search is conducted in a downstream direction, however, if the new point is upstream of the previous point, the tape is backspaced six lines and bracketing is again attempted. If the tape is searched one hundred lines downstream of the starting point, or if the flow field boundary is reached, the tape is rewound and the search is started again.
3. If the body point is bracketed, four to eight of the surrounding characteristic points are used in a linear interpolation to determine Mach number, flow angle, and entropy.

Three flags are used as indicators of the results of the tape search.

1. IFLAG = 1 - indicates boundary has not been read in.
= 2 - indicates boundary has been read in.
2. JFLAG = 1 - indicates last start line point was not in flow field.
= 2 - indicates last start line point was in flow field.
3. KFLAG = 1 - indicates current start line point is not in flow field.
= 2 - indicates current start line point is in flow field.

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SUBROUTINE NAME: KIKOFF

DESCRIPTION

This subroutine allows control to return to the Main program if an error in the calculation is encountered, and controls the execution of multiple cases.

CALLING SEQUENCE

CALL KIKOFF

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/QUIT/
DRIVER

METHOD OF SOLUTION

Not applicable.

SUBROUTINE NAME: LIMITS

DESCRIPTION

This subroutine tests the new boundary point to determine if it is within the limits of the current boundary equation. Depending on the test, the options are:

1. use the current boundary equation,
2. advance to the next boundary equation, or
3. the current equation is the last one specified.

CALLING SEQUENCE

CALL LIMITS (I, K, ITYPE, IOK)

where (I, K) represents the location of the boundary point in the PHO array, (ITYPE) tells if an upper or lower boundary is to be considered, and (IOK) is a control indicating if option 1, 2, or 3 is to be used.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/DATAR/
BOUND

METHOD OF SOLUTION

The radius (RMAX) and boundary angle (THETAMAX) at the limiting axial value (XMAX) is calculated in (BOUND). (RMAX) or (XMAX) is compared to (R) or (X) for the point in question. The results of the comparison determine if option 1, 2 or 3 is to be used.

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SUBROUTINE NAME: LIPIN

DESCRIPTION

LIPIN calculates information for the starting line points when the simplified straight start line option is used (i. e. , when $ICON(2) \neq 2$).

CALLING SEQUENCE

CALL LIPIN (COOR, S, INTOT, DELM)

where (COOR) is the starting line information array, (S) is the entropy level of the start line, (INTOT) is the total number of input points specified (50 MAX), and (DELM) is Mach number gradient along the start line.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/INPUT/
COMMON/CONTRL/
RGVOFM
UOFV

METHOD OF SOLUTION

The start line input data is divided into the specified number of increments. Radial gradients in Mach number, X , θ , are calculated. A circular arc transformation is applied to the input line data points to concentrate the points near the outer boundary.

SUBROUTINE NAME: MASCONDESCRIPTION

This subroutine calculates the Mach number distribution at an area downstream of the throat such that total mass flow is conserved. Mass flow, calculated at the throat, is used as the constant for comparison.

CALLING SEQUENCE

CALL MASCON (E, SE, DELM)

where (E) is the input line array (CORLIP), (SE) is the input line entropy level, and (DELM) is the Mach number gradient along the start line.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/

RGVOFM

RHOFEM

ERRORS

EMOFV

ITSUB

METHOD OF SOLUTION

The mass flow rate at the throat (\dot{m}^*) is calculated. This (\dot{m}^*) is compared to that at the input line location for an initial Mach number distribution. The Mach number distribution is then perturbed until mass flow is conserved.

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SUBROUTINE NAME: MASSCK

DESCRIPTION

This subroutine keeps a running check on the mass flow. Mass flow at the starting line is calculated and compared with that crossing each characteristic line downstream.

CALLING SEQUENCE

CALL MASSCK (ILAST, ISTART, K)

where (ILAST) is the last point on the characteristic line, (ISTART) is a counter for characteristic lines which emanate from the start line, and (K) represents the characteristic line under consideration.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/
COMMON/INPUT/
COMMON/CON RL/
COMMON/STEPCL/
COMMON/FORCE/
COMMON/WTSASF/
FABLE
EMOFV
RHOFEM
UOFV

METHOD OF SOLUTION

The mass flow through the start line is calculated and stored. Mass flow through lines downstream is calculated and these values compared with the initial value. A percent change in mass flow is printed for each characteristic line. The total mass flow passing under each point on a characteristic line is stored so the mass flow can be written on the output tape to permit streamline tracing.

SUBROUTINE NAME: MOC SOL

DESCRIPTION

This subroutine provides all two dimensional or axisymmetric method-of-characteristics solutions. The new point being solved for may be one of five possible types:

1. interior point
2. upper wall point
3. upper free boundary point
4. lower wall point
5. lower free boundary point

CALLING SEQUENCE

CALL MOC SOL (I, K, I1, K1, I2, K2, IFLAG, ITYPE)

where (I, K) identifies the storage location for the new point to be computed, (I1, K1) identifies the right running (or upper boundary) known point, and (I2, K2) identifies the left running (or lower boundary) known point. (IFLAG) is an error indicator and (ITYPE) selects the type calculation.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	BOUND
COMMON/CRITER/	ROTERM
COMMON/DATAR/	VOFEM
COMMON/GASCON/	RGM OFP
FABLE	FNEWTN
INRSCT	TOFV
POFEM	UOFV
EMOFV	RHOFEM
	ERRORS

METHOD OF SOLUTION

The four characteristic equations are written as a function of five variables (R, X, θ , V, S). An additional relationship is obtained by assuming

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the entropy (S) varies linearly between known data points. Using these characteristic equations in finite difference form, the routine solves for a new mesh point, knowing two mesh points of opposite family.

The solution is begun by setting the average values of properties over the step length equal to the known values at the base points. Subsequent passes in the iterative solution result in "updated" average values. The iterative solution is continued until the desired convergence on velocity or flow angle is reached or until the maximum number of iterations is exceeded.

For a detailed derivation of the characteristic equations and a description of their application in finite difference form to the solution of the characteristic mesh, see Vol.III, Section 6.

SUBROUTINE NAME: MONO

DESCRIPTION

This subroutine determines if the characteristic point locations are monotonic along left or right running lines.

CALLING SEQUENCE

CALL MONO (I1, J1, I2, J2, I3, K3, IOK)

where (I1, J1), (I2, J2), (I3, K3) designate the right running base point, the left running base point, and the new characteristic point, respectively. IOK is a flag returned to the calling program which is (0) if solution is monotonic, (1) if a non-monotonic condition has occurred along the right running characteristic, and (2) if one has occurred along a left running line.

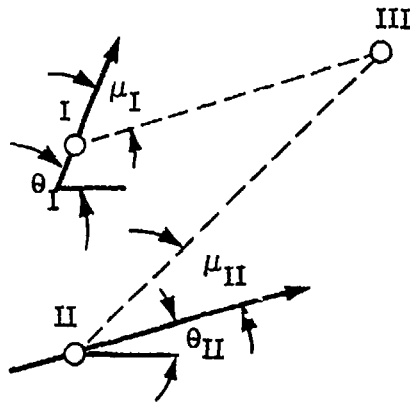
UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/

UTILITY - None

METHOD OF SOLUTION

Envelope shock waves are detected in a method-of-characteristics solution by crossing of characteristic lines which, mathematically, causes a discontinuity in the flow properties. This discontinuity is interpreted as a shock wave. This routine is supplied the two base points and the resultant new mesh point. Using this information, a discontinuity, if it exists, is detected.



Now

$$\hat{r}_{III} = \hat{r}_{II} + \lambda_I \left\{ \cos(\bar{\theta}_I - \bar{\mu}_I) \hat{i} + \sin(\bar{\theta}_I - \bar{\mu}_I) \hat{j} \right\}$$

and

$$\hat{r}_{III} = \hat{r}_{II} + \lambda_{II} \left\{ \cos(\bar{\theta}_{II} + \bar{\mu}_{II}) \hat{i} + \sin(\bar{\theta}_{II} + \bar{\mu}_{II}) \hat{j} \right\}$$

Effectively, this routine checks the sign of $\lambda_{I, II}$ and sets IOK accordingly.

e.g., if $\lambda_I, \lambda_{II} \leq 0$ IOK = 0
 if $\lambda_I < 0$ IOK = 1
 if $\lambda_{II} < 0$ IOK = 2

D
D
D
D
D
D
D
D
D
D

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SUBROUTINE NAME: OUT

DESCRIPTION

This sub routine writes the calculated data at characteristic points along with the corresponding title and headings.

CALLING SEQUENCE

CALL OUT (I1, I2, K)

where (I1, I2) refer to the point numbers of the points to be output (any number of points may be output at one time). (K) represents the current characteristic line (takes on the value 1 or 2).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	EMOFV
COMMON/DATAR/	UOFEM
COMMON/GASCON/	PCFEM
COMMON/HEAD/	RHOFLM
PAGE	TOFEM
FABLE	VOFEM
	ESHOCK

METHOD OF SOLUTION

Not applicable.

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SUBROUTINE NAME: OUTBIN

DESCRIPTION

This subroutine writes the calculated characteristic point data on the binary output tape. This is done for any number of characteristic points.

CALLING SEQUENCE

CALL OUTBIN (I1, I2, J)

where (I1, I2) identifies the range of points to be written on tape (I1 is first point, I2 is last). (J) represents the current characteristic line (1 or 2).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/
COMMON/WTSAVE/
COMMON/ITAPE/
FABLE
EMOFV

METHOD OF SOLUTION

Not applicable.

SUBROUTINE NAME: OVEREXDESCRIPTION

This subroutine solves for the shock angle at the nozzle lip when the flow is over expanded. Provisions are made to calculate the shock angle for an upper or lower lip point. Real gas effects are considered in calculating flow properties downstream of the shock.

CALLING SEQUENCE

CALL OVEREX (PB, I, K, ITYPE)

where (PB) is the freestream pressure at the boundary, (I, K) defines the location of the lip point in the characteristic data (PHO) array and (ITYPE) indicates whether an upper or lower boundary is to be considered.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/

FABLE

EMOFV

ESHOCK

POFEM

ITSUB

UOFV

METHOD OF SOLUTION

An initial shock angle is assumed. This shock angle is perturbed in ITSUB and the result used to calculate flow properties downstream of the shock, including static pressure. The calculated static pressure is compared with the boundary pressure and the difference is driven sufficiently close to zero to satisfy convergence criteria.

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SUBROUTINE NAME: PAGE

DESCRIPTION

This subroutine page ejects and writes the header comments and page number on each page of printout.

CALLING SEQUENCE

CALL PAGE (LCNT)

where (LCNT) is a counter which monitors the number of lines of printed output per page. (LCNT) is re-initialized in PAGE.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/HEAD/
COMMON/CONTRL/
UTILITY - None

METHOD OF SOLUTION

When the maximum number of lines per page (55) have been output, (PAGE) is called to page eject. It then prints the identifying information and the page number, increments the page number and re-initializes the line counter.

SUBROUTINE NAME: PHASE1

DESCRIPTION

This subroutine provides the necessary logic to successively employ the proper calculation at the proper time in order to describe the entire characteristic mesh. Direction is given to calculate the flow field throughout the nozzle and plume, and termination is achieved when a right running shock intersects the boundary or problem limits have been reached.

CALLING SEQUENCE

CALL PHASE1 (IFINIS)

where (IFINIS) is a flag to bring in additional logic routines for restarting the characteristic solution for reflecting a shock which has intersected the axis of symmetry.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	UOFV	ESHOCK
COMMON/GASCON/	ITERM	SAVER
COMMON/DATAR/	RGVOFM	
COMMON/ITAPE/	HYPER	
COMMON/INPUT/	POFEM	
COMMON/DEL/	EMOFV	
COMMON/STEP/	RGMOFP	
COMMON/WHICH/	VOFEM	
COMMON/FINITE/	THETPM	
FABLE	MONO	
OUT	TURN	
THRUST	OVEREX	
OUTBIN	ERRORS	
MOC SOL	SHOCK	
LIMITS	MASSCK	
BOUND	ICHECK	
PRANDT		

METHOD OF SOLUTION

In general terms, the flow properties at an unknown characteristic point may be expressed as some operation (ψ) on some number ($\phi_1, \phi_2, \dots, \phi_m$) of known points. These operations (ψ) differ according to the type of unknown point to be calculated. Presently, the six types of unknown points dealt with or six operations (ψ) performed are:

1. starting line point (ψ_0)
2. interior point (ψ_I)
3. boundary point (upper or lower) (ψ_B)
4. attached shock point (ψ_{AS})
5. shock point (ψ_S)
6. Prandtl-Meyer point (upper or lower, solid or free) (ψ_{PM})

Basically, PHASE1 contains the fixed point arithmetic necessary to perform the above mentioned calculations. Through this system of fixed point arithmetic, the necessary types of calculations are performed on the proper known characteristic points to produce the new characteristic point. For a detailed description of the fixed point arithmetic and examples of its use, see Appendix.

SUBROUTINE NAME: PLUMIN

DESCRIPTION

This subroutine reads in the input data (input via cards) necessary to perform the method-of-characteristics solution. This input information is routed by PLUMIN to various supporting routines depending on the options selected.

CALLING SEQUENCE

CALL PLUMIN

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	GASRD	VOFEM
COMMON/CUTFO/	BOUND	RGMOFB
COMMON/DATAR/	LIPIN	CHECK
COMMON/GASCON/	AOASTR	ITSUB
COMMON/HEAD/	MASCON	ERRORS
COMMON/INPUT/	RGVOFM	VISCUS
COMMON/STPC	UOFV	
COMMON/POINTS/	POFEM	
COMMON/DIVCRI/	PLMOUT	
COMMON/QUIT/	THROAT	
COMMON/WHICH/	SOLVE	

METHOD OF SOLUTION

Not applicable.

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SUBROUTINE NAME: PLMOUT

DESCRIPTION

This subroutine prints the data read by (PLUMIN).

CALLING SEQUENCE

CALL PLMOUT (KP, LCNT)

where (KP) is a control parameter which is set in PLUMIN, and (LCNT) is the printed line counter.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/CUTFO/
COMMON/TAPEFO/
COMMON/DATAR/
COMMON/GASCON/
COMMON/HEAD/
COMMON/INPUT/
COMMON/DIVCRI/
PAGE
FABLE
EMOFV

METHOD OF SOLUTION

Not applicable.

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FUNCTION NAME: POFEMDESCRIPTION

This function computes the local static pressure as a function of Mach number and entropy.

CALLING SEQUENCE

$$P = \text{POFEM}(\text{EM}, S)$$

where (P) is the resultant static pressure found from the Mach number (EM) and entropy (S). NOTE: The appropriate values of the gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

UTILITY - None

METHOD OF SOLUTION

Thermally perfect gas relationships are used to find the pressure.

$$p = p_o e^{-S/R} \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{\gamma}{\gamma - 1}}$$

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SUBROUTINE NAME: PRANDT

DESCRIPTION

This subroutine computes the Prandtl-Meyer expansion angle for a given boundary angle and divides this angle into a series of expansion "rays" (unless the number of rays has been specified in the input). The flow properties at each angular increment are set and stored in the Characteristic Data (PHO) array.

CALLING SEQUENCE

CALL PRANDT (I, J, THETAB, NPM, IFLAG, ITYPE)

where

(I) - represents the corner point

(J) - indicates a characteristic line

(THETAB) - is the boundary angle

(NPM) - number of Prandtl-Meyer increments (calculated in PRANDT)

(IFLAG) - error flag

(ITYPE) - indicates if upper (2) or lower (1) boundary

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CRITER/

COMMON/DATAR/

COMMON/GASCON/

COMMON/STEP/

COMMON/CONTRL/

FABLE

THETPM

UOFV

METHOD OF SOLUTION

The routine is entered with known flow properties at the point of discontinuity along with the known corner and boundary flow angles. From the known angles and the preset number of degrees per ray, the number of

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increments is calculated. The distribution of P-M rays is then adjusted by a weighting function. Subroutine (THETPM) is entered with known initial conditions and the number of degrees per ray and returns with a velocity. These new conditions are then set into the (PHO) array.

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SUBROUTINE NAME: READB

DESCRIPTION

Subroutine READB reads the position of the boundary points of the flow field.

This information is read from the binary output tape for setting up the start line for automatically restarting a reflected shock.

Subroutine JWBTS uses this to determine boundary position of flow field.

CALLING SEQUENCE

CALL READB (X,R,ITOT1)

X = X coordinate of last point on characteristic line

R = R coordinate of last point on characteristic line

ITOT1 = Number of points on the line

UTILIY ROUTINES AND COMMON REFERENCES

None

METHOD OF SOLUTION

Not applicable

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SUBROUTINE NAME: READFDESCRIPTION

SUBROUTINE READF reads one characteristic line from flow field tape and saves the following data at each point:

1. X position of the point,
2. R position of the point,
3. Mach number at the point,
4. Flow angle at the point,
5. Entropy at the point,
6. Velocity at the point.

This information is read from a binary output tape for setting up the start line for the automatic restart of a reflected shock.

CALLING SEQUENCE

CALL READF (J, ITOT1)

J - number of characteristic line
ITOT1 - number of points in characteristic line

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DUMPCO/
UTILITY - None

METHOD OF SOLUTION

Not applicable

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FUNCTION NAME: RGMOFP

DESCRIPTION

This subroutine finds Mach number as a function of pressure, O/F ratio and entropy. The difference between this routine and EMOFP is that in this case the gas properties are not known prior to entry.

CALLING SEQUENCE

EM = RGMOFP (P, OF, S)

where (EM) is the resultant Mach number, (P) is the local static pressure, while (S) is the local entropy, and (OF) is the local O/F ratio.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	COMMON/ DATAR/
COMMON/GASCON/	COMMON/TAPEFO/
POFEM	VOFEM
EMOFV	EMOFP
ITSUB	ERRORS
FABLE	

METHOD OF SOLUTION

The real gas tables have, as independent variables, OF ratio, entropy and velocity. If the velocity is not known, an iterative solution must be employed to find Mach number from pressure, entropy, and OF ratio.

FUNCTION NAME: RGVOFM

DESCRIPTION

This subroutine finds velocity as a function of Mach number, entropy and O/F ratio. The difference between this routine and VOFEM is that the gas properties are not known prior to entry.

CALLING SEQUENCE

$$V = \text{RGVOFM}(\text{OF}, \text{S}, \text{EM})$$

where V is the resultant velocity computed from OF ratio (OF), entropy (S), and Mach number (EM).

UTILITY ROUTINES AND COMMON REFERENCES

FABLE	COMMON/CONTRL/
VOFEM	COMMON/TAPEFO/
EMOFV	COMMON/DATAR/
ITSUB	
ERRORS	

METHOD OF SOLUTION

The real gas tables have, as independent variables, OF ratio, entropy and velocity. If the velocity is not known, an iterative solution must be employed to find the velocity from Mach number, OF ratio and entropy.

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FUNCTION NAME: RHOFEM

DESCRIPTION

This function computes the local density as a function of Mach number and entropy.

CALLING SEQUENCE

RHO = RHOFEM (EM, S)

where RHO is the resultant density found from local Mach number and local entropy. NOTE: The appropriate values of the gas properties must be stored in common upon entry to this routine.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/
POFEM

METHOD OF SOLUTION

Thermally perfect gas relationships are used to find the density.

$$\rho = \rho_o \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-\left(\frac{1}{\gamma - 1}\right)}$$

FUNCTION NAME: ROTERMDESCRIPTION

This routine computes the geometrical factor (F_I, F_{II}) used in the axisymmetric term of the capability equation and as an interpolation parameter.

CALLING SEQUENCE

$F = \text{ROTERM}(\text{THETA}, \text{DELTA}, \text{EMU}, \text{R3}, \text{RI})$

where (THETA) is $\bar{\theta}_I$ or $\bar{\theta}_{II}$ (flow angles of the known points)

(DELTA) selects quadrant

(EMU) is $\bar{\mu}_I$ or $\bar{\mu}_{II}$ (Mach angles of the known points)

(R3) is \bar{r}_{III} or x_{III} (coordinates of new point)

(RI) is r_I or x_I (coordinates of known point)

UTILITY ROUTINES AND COMMON REFERENCES

None

METHOD OF SOLUTION

The method-of-characteristics solution uses this routine to determine a coefficient needed in its solution. This term (see Equation (6-29), Section 6 of Reference 1) can be written as:

$$F = \frac{|\sin \mu| (d_{I,II} - d)}{\sin \left(\frac{\pi}{4} + \delta (\bar{\theta} + \bar{\mu} - \frac{\pi}{4}) \right)}$$

By the proper choice of d (r or x), δ and the sign of μ , indeterminate forms are eliminated in the evaluation.

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SUBROUTINE NAME: SAVER

DESCRIPTION

This routine saves the flow properties at the nozzle lip for setting up the start line for the automatic restart of the reflected shock case.

CALLING SEQUENCE

CALL SAVER (I, K)

where I is the lip point number on the characteristic line, and

K is the characteristic line on which the lip point was found.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/

COMMON/SHCKPT/

UTILITY - None

METHOD OF SOLUTION

Not applicable

SUBROUTINE NAME: SETUPDESCRIPTION

For the automatic restart of a reflected shock this subroutine locates and distributes the start line points along a straight line from the nozzle lip or first point on the original start line to the point where the shock has intercepted the axis.

CALLING SEQUENCE

CALL SETUP (COOR, INTOT)

where COOR is the starting line information array, and
INTOT is the number of start line points specified.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/INPUT/
COMMON/CONTRL/
UTILITY - None

METHOD OF SOLUTION

The reflected shock start line data is divided into the specified number of increments. Radial gradients in R, X and θ are calculated. A circular arc transformation is applied to the input line data to concentrate the points near the outer boundary.

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FUNCTION NAME: SHOCK

DESCRIPTION

This subroutine iteratively adjusts the shock strength in order to satisfy the oblique shock relations and the flow field properties simultaneously. The six different options are:

1. interior right running shock wave
2. interior left running shock wave
3. right running shock wave at wall
4. left running shock wave at wall
5. right running shock reflected from boundary
6. left running shock reflected from boundary

NOTE: Options 2, 4 and 6 currently not executed.

CALLING SEQUENCE

CALL SHOCK (IN, KN, IKL, IN1, JN, IJH, I8FIN, I7FIN, IFLAG, ITYPE, IOPT)

where (IN, KN) is the location of the virtual point
IKL is the first point on the KN array
(IN1, JN) is the location of the known shock point
IJH is the last point on the JN array
I8FIN is the final location of the upstream shock point
I7FIN is the final location of the base point on the downstream side
IFLAG is an error flag
ITYPE selects the type of calculation
11 for case (1)
12 for case (2)
21 for case (3)
ITYPE = 22 for case (4)
31 for case (5)
32 for case (6)
IOPT = Parameter for controlling direction and magnitude of perturbations during iteration.

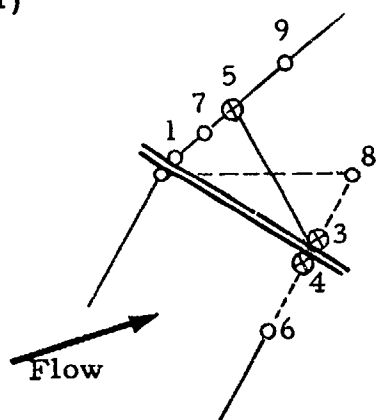
UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/	ERRORS
COMMON/CRITER/	UOFV
COMMON/GASCON/	MOSCOL
COMMON/DATAR/	ROTERM
COMMON/IRFEC/	ITSUB
INRSCT	ESHOCK
FABLE	

METHOD OF SOLUTION

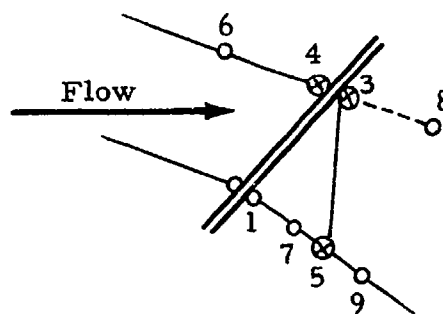
This subroutine is used to calculate the properties across an oblique shock wave as a function of the local characteristic lattice. In its operation, this routine instructs the calling routine as to the necessity of adjusting the counting scheme for network construction due to the presence of the shock wave. Diagrams for the six options are given below.

(1)



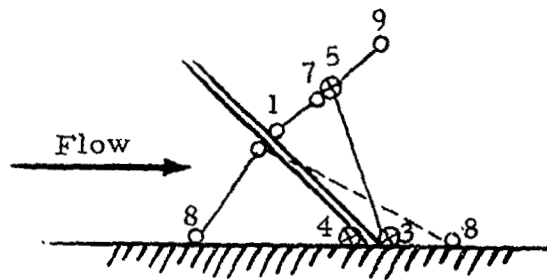
Case (1), ITYPE = (11)

(2)

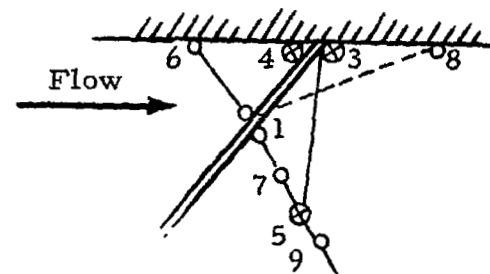


Case (2), ITYPE = (12)

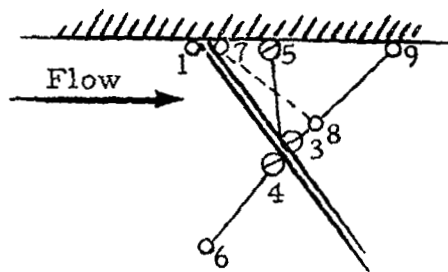
(3)



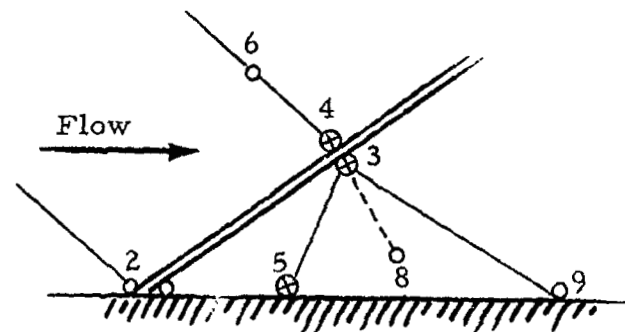
Case (3), ITYPE = (21)



CASE (4), ITYPE = (22)



Case (5), ITYPE = (31)



Case (6), ITYPE = (32)

SUBROUTINE NAME: SOLVEDESCRIPTION

This subroutine solves for the coefficients of the nozzle wall cubic equation described by points input to the program.

CALLING SEQUENCE

CALL SOLVE (ITYPE, M, YP)

where ITYPE determines if the solution is for an upper or lower wall,
M is the total number of input points describing the wall, and
YP is the slope at the first point describing the wall.

UTILITY ROUTINES AND COMMON REFERENCES

A series of third order curve fits is performed. Each curve fit uses 3 consecutive input points and the slope at the first input point. The coefficients for a polynomial wall equation are then determined from each curve fit.

METHOD OF SOLUTION

Not applicable.

LMSC/HREC D162220-IV

SUBROUTINE NAME: SWITCH

DESCRIPTION

This routine transfers the upper boundary equations into the lower boundary array and the lower boundary equations into the upper boundary array. The appropriate signs on the equation coefficients are also changed so that the problem can be automatically restarted for a reflected shock case.

CALLING SEQUENCE

CALL SWITCH

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/DATAR/
UTILITY - None

METHOD OF SOLUTION

Not applicable.

SUBROUTINE NAME: TABLEDESCRIPTION

This subroutine utilizes real or ideal gas information obtained from a master tape or input cards to calculate properties locally in the flow. The maximum size of the array used by (TABLE) is limited to five gas properties (V , R , γ , T_o , P_o) at thirteen velocity "cuts" for each of two entropy cuts and 10 O/F cuts.

CALLING SEQUENCE

CALL TABLE (SS, VV, IF)

where (SS) is the local entropy, (IF) is the O/F table of interest and (VV) is the local velocity at the point of interest.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/XSICOM/
COMMON/CONTRL/
COMMON/DATAR/
COMMON/GASCON/
COMMON/FAB/
TOFV
POFEM
EMOFV

METHOD OF SOLUTION

The routine is entered with an O/F table (IF), the local entropy (SS) and velocity (VV). A test is then made to determine if the gas is real or ideal. If the test indicates an ideal gas, the local properties are set to those stored in the (TAB) common array. If the test indicates real gas, a double interpolation scheme is utilized to locate gas properties between tabulated values of velocity and entropy. In the case of an entry beyond the range of the tables, an ideal gas extrapolation from the last table value is made to determine the gas properties.

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SUBROUTINE NAME: TAPMOV

DESCRIPTION:

This subroutine moves the binary flow field tape through the gas property data to the start of the flow field information.

CALLING SEQUENCE

CALL TAPMOV

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/IRECD/
UTILITY - None

METHOD OF SOLUTION

Not applicable.

LMSC/HREC D162220-IV

SUBROUTINE NAME: THETPMDESCRIPTION

This subroutine performs a numerical integration to calculate properties through a Prandtl-Meyer expansion. Either the case of known final velocity or known final expansion angle may be handled.

CALLING SEQUENCE

CALL THETPM (OF, S, DELTA, VF, VI, IT, ITYPE)

where (OF) is the local OF ratio
 (S) is the local entropy level
 (DELTA) is the total expansion angle
 (VF) is the final velocity downstream of the expansion
 (VI) is the initial velocity upstream of the expansion
 (IT) is a control parameter indicating if expansion to a solid wall or free boundary is taking place
 (ITYPE) indicates if upper (2) or lower (1) boundary

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/	ITSUB
COMMON/STEP/	TOFV
FABLE	ERRORS

METHOD OF SOLUTION

The integral equation

$$\int_{V_1}^{V_F} \sqrt{M^2 - 1} \frac{dV}{V} - \Delta\theta = f(V_F) = 0$$

$$(M^2 = V^2/\gamma RT)$$

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is solved knowing either the final velocity (V_F) or the expansion angle ($\Delta\theta$). As can be seen, if the final velocity (V_F) is known, the integration progresses straightforwardly to a solution. However, if the expansion angle is known, an iterative procedure must be employed to pick the velocity which produces the desired expansion angle.

SUBROUTINE NAME: THROATDESCRIPTION

This subroutine computes the nozzle throat equation coefficients.

CALLING SEQUENCE

CALL THROAT (ITYPE, YP)

where (ITYPE) is a 1 for an upper wall throat and a 2 for a lower wall throat. (YP) is the slope of the first point on the next curve.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/DATAR/

COMMON/POINTS/

UTILITY - None

METHOD OF SOLUTION

The nozzle throat radius, radius of curvature, divergence angle and an axial coordinate shift are used to find the coefficients for the conic equation:

$$R = A \left\{ \sqrt{B + CX + 2DX^2} + E \right\}$$

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SUBROUTINE NAME: THRUST

DESCRIPTION

This routine computes the vacuum thrust produced by a two-dimensional or axisymmetric nozzle. Addition of the thrust at the throat and the integrated pressure along the nozzle wall yields the final thrust.

CALLING SEQUENCE

CALL THRUST (I, K, I1, J1, ITYPE, ICALC)

where (I, K) designates the unknown characteristic point and (I1, J1) is the known characteristic point. (ITYPE) specifies if the point is on the upper or lower boundary and (ICALC) is a counter with the values of 1, 2 or 3. (1 specifies integration at the throat, 2 - along the nozzle and 3 - at the exit.)

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CONTRL/
COMMON/DATAR/
COMMON/FORCE/
COMMON/INPUT/
COMMON/STEPCL/
FABLE
EMOFV
POFEM
RHOFEM

METHOD OF SOLUTION

Thrust is found by first computing the momentum thrust in the sonic area or throat of the nozzle. The static pressure is then integrated along the nozzle wall and the total thrust found by summation of the pressure and momentum terms. Inclusion of a factor in the incremental force term accounts for either two-dimensional or axisymmetric flow.

FUNCTION NAME: TOFEMDESCRIPTION

This function computes the local static temperature as a function of Mach number. The gas properties at the point of interest are known prior to entry. TOFEM and TOFV are quite similar; the difference being if Mach number or velocity is the known quantity.

CALLING SEQUENCE

$$T = \text{TOFEM}(\text{EM})$$

where (T) is the one-dimensionally calculated local static pressure which exists at the Mach number (EM).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

METHOD OF SOLUTION

The calorically perfect gas relationship

$$T = \frac{T_o}{1 + \frac{\gamma - 1}{2} M^2}$$

is solved for static temperature at the local Mach number.

LMSC/HREC D162220-1V

FUNCTION NAME: TOFV

DESCRIPTION

This function computes the local static temperature as a function of velocity. The gas properties at the point of interest are known prior to entry. TOFV and TOFEM are quite similar; the difference being if Mach number or velocity is the known variable.

CALLING SEQUENCE

$$T = \text{TOFV}(V)$$

where (T) is the one-dimensionally calculated local static pressure which exists at the velocity (V).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

UTILITY - None

METHOD OF SOLUTION

The calorically perfect gas relationship

$$T = T_o - \frac{V^2}{2R} \left(\frac{\gamma - 1}{\gamma} \right)$$

is solved for static temperature at the local velocity.

LMSC/HREC D162220-IV

SUBROUTINE NAME: TURNDESCRIPTION

This subroutine solves for a shock wave which has a known turning angle (δ). A condition of known turning angle exists when the flow is turned through a compression corner on a solid boundary. Real gas effects are considered in calculating conditions downstream of the shock.

CALLING SEQUENCE

CALL TURN (PU, PD, DELTA, IFLAG)

where (PU, PD) represent flow conditions upstream and downstream of the shock, (DELTA) is the turning angle, and (IFLAG) indicates if the solution will converge or not.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/CRITER/	ESHOCK
COMMON/CONTRL/	ITSUB
COMMON/FINITE/	CONE
FABLE	UOFV
EMOFV	
UOFEM	

METHOD OF SOLUTION

An initial shock angle is guessed. This shock angle is used to calculate a turning angle. The calculated turning angle is compared to the known turning angle and successive iterations on shock angle are performed until the turning angle difference is sufficiently close to zero.

LMSC/HREC D162220-IV

FUNCTION NAME: UOFEM

DESCRIPTION

This function computes the Mach angle at a local Mach number. A test is made to ensure that the Mach number is greater than one; prior to the calculation.

CALLING SEQUENCE

EMU = UOFEM (EM)

where (EMU) is the Mach angle which exists at the local Mach number (EM).

UTILITY ROUTINES AND COMMON REFERENCES

ERRORS COMMON - None
KIKOFF

METHOD OF SOLUTION

The following equation

$$\mu = \tan^{-1} \left(\frac{1}{\sqrt{M^2 - 1}} \right)$$

is solved for the local Mach angle.

FUNCTION NAME: UOFV

DESCRIPTION

This function computes the Mach angle at a local velocity.

CALLING SEQUENCE

EMU = UOFV (V)

where (EMU) is the Mach angle which exists at the local velocity (V).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON - None

UOFEM

EMOFV

METHOD OF SOLUTION

The local velocity is converted into a Mach number using (EMOFV). Function (UOFEM) is then entered with the calculated Mach number and the Mach angle obtained from the following equation.

$$\mu = \tan^{-1} \left(\frac{1}{\sqrt{M^2 - 1}} \right)$$

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SUBROUTINE NAME: VISCUS

DESCRIPTION

This subroutine calculates the laminar or turbulent boundary layer thickness and velocity distribution at the nozzle exit. This boundary layer adjustment is made on the exit plane starting line. Only the supersonic portion of the boundary layer is considered.

CALLING SEQUENCE

CALL VISCUS (N, NBL, XL, CU)

where (N) is the power of the velocity profile ($V/V_{\text{edge}} = (y/y_{\text{edge}})^{1/N}$). (NBL) is number of boundary layer points specified. (XL) is a characteristic length (usually the nozzle length). (CU) is a conversion factor for mixed units of length in the boundary layer calculation.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/INPUT/	EMOFV
COMMON/CONTRL/	TOFEM
COMMON/GASCON/	POFEM
FABLE	VOFEM
	UOFV

METHOD OF SOLUTION

The number of starting line points within the supersonic portion of the boundary layer is specified. The velocity profile for a laminar or turbulent boundary layer is calculated and distributed to the starting line points. These points are then transferred to a right running characteristic line and the remaining inviscid portion of the starting line is attached.

FUNCTION NAME: VOFEM

DESCRIPTION

This function computes velocity as a function of Mach number. Ideal gas relations are used and the gas properties are known prior to entry.

CALLING SEQUENCE

$$V = \text{VOFEM}(\text{EM})$$

where (V) is the local velocity which corresponds to the local Mach number (EM).

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/
TOFEM

METHOD OF SOLUTION

The ideal gas relationship

$$V = \sqrt{\frac{R\gamma(T_o - T)}{\left(\frac{\gamma - 1}{2}\right)}}$$

is solved for velocity. Local static temperature (T) is obtained from the input Mach number.

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SUBROUTINE NAME: WEAK

DESCRIPTION

This subroutine determines the independent variables (SD, VD) downstream of a weak oblique shock. The gas properties upstream of the shock are known prior to entry.

CALLING SEQUENCE

CALL WEAK (OF, SU, VU, ERS, DELTA, SD, VD)

where (OF) is the upstream O/F ratio, (SU, VU) are the upstream entropy and velocity, (EPS, DELTA) are the shock angle and turning angle, and (SD, VD) are the downstream entropy and velocity.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/
TABLE
EMOFV
POFEM
RHOFEM
ENTROP
DELTAF

METHOD OF SOLUTION

From the known upstream entropy and velocity, the local gas properties, pressure, density, and upstream Mach number are calculated. The entropy rise across the shock is added to the upstream entropy to get total downstream entropy. Downstream velocity is calculated from the following relationship.

$$V_D = \frac{V_u \cos (\xi)}{\cos (\xi - \delta)}$$

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FUNCTION NAME: WOFADESCRIPTION

This function computes the weight flow per unit area as a function of Mach number. This calculation is only used in function AOASTR.

CALLING SEQUENCE

WEIGHT FLOW = WOFA (EM)

where (EM) is the local Mach number.

UTILITY ROUTINES AND COMMON REFERENCES

COMMON/GASCON/

UTILITY - None

METHOD OF SOLUTION

Weight flow per unit area (\dot{W}/A) is calculated from ideal gas relations. The equation used is

$$\frac{\dot{W}}{A} = \sqrt{\frac{\gamma}{RT_o}} \left\{ \frac{P_o M}{\left[1 + \frac{\gamma - 1}{2} M^2 \right]^{\frac{\gamma + 1}{2(\gamma - 1)}}} \right\}$$

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3.5 PROGRAM OUTPUT

This subsection contains a description of the output scheme utilized by the program and a description of the error messages printed out by the program.

3.5.1 Description of Program Output

The methods of characteristics program output is organized in a logical fashion with the data presented in an easily understood form. The initial pages consist of a printout of the input data including the real gas tables obtained from the master tape. Characteristic data are organized along left-running characteristic lines with all the pertinent information printed for each characteristic point on each characteristic line. Numbered flags on the example printout sheets (pp. 3-124 through 3-127) correspond to numbered comments listed below.

GROUP 1 - IDENTIFICATION

- ① Case Number: Appears on each page - may be a maximum of five digits.
- ② Title: Identifies particular run, appears on each page and may be 72 spaces.

GROUP 2 - RUN CONTROL

- ③ Run Control Parameters: These 16 parameters control the execution of the program according to the options selected. (See Input/Output FORTRAN symbols section for explanation of individual parameters.)

GROUP 3 - BOUNDARY EQUATIONS (See Input/Output FORTRAN Symbols for detailed description.)

- ④ Type Equation: Identifies type of boundary equation selected. (1 - conic, 2 - poly, 3 - free bound)
- ⑤ ITRANS: Indicates if a discontinuity follows this equation, 0 - no discontinuity, 1 - discontinuity).
- ⑥ Coefficients: Apply to upper or lower boundary equations.
- ⑦ XMAX: Maximum value of (x) for which present equation applies.

GROUP 4 - GAS IDENTIFICATION

- ⑧ Gas Identification: Identifies gas on master tape for which gas table is printed.

GROUP 5 - REAL/IDEAL GAS PROPERTIES (See Input/Output FORTRAN Symbol section)

- ⑨ O/F Ratio: The O/F ratio for the particular table.
- ⑩ Entropy Cuts: May be two maximum for each O/F table, value is relative to first entropy level in each table.
- ⑪ Velocity Cuts: May be 13 maximum at each entropy cut.
- ⑫ "Gas Constant": Value associated with the particular velocity, entropy and O/F ratio.
- ⑬ Isentropic Exponent: Value associated with the particular velocity, entropy and O/F ratio.
- ⑭ Static Temperature: Value associated with the particular velocity, entropy and O/F ratio.
- ⑮ Static Pressure: Value associated with the particular velocity, entropy and O/F ratio.

Note: Ideal gas format is similar (O/F) is as read in from card, (S) and (V) are generally zero and only one value of R , γ , T_o , P_o is printed.

GROUP 6 - STARTING LINE INFORMATION (See Input/Output FORTRAN Symbol Section)

- ⑯ R: Radial distance to characteristic point (may be any unit of length or non-dimensional).
- ⑰ X: Axial distance to characteristic point (may be any unit of length or non-dimensional).

Note: The only restriction on units for X and R is that they be consistent, however thrust and mass flow calculations assume feet.

- ⑮ Mach Number: Local value at particular R and X location (may be any supersonic value).
- ⑯ Flow Angle: Local value at particular R and X location (degrees).
- ⑰ Entropy: Local value at particular R and X location ($\text{ft}^2/\text{sec}^2 \cdot ^\circ\text{R}$).
- ⑱ O/F Ratio: Local value at particular R and X location.

Note: The starting line may be obtained using various options (see Input Guide); however, the format on the printout remains the same.

GROUP 7 – MESH CONTROL CRITERIA (See Input/Output FORTRAN Symbol Section DIV(1) – DIV(6))

- ⑳ DLI: Length insertion criteria.
- ㉑ DLL: Length deletion criteria.
- ㉒ DMI: Mach number insertion criteria.
- ㉓ DML: Mach number deletion criteria.
- ㉔ DTI: Flow angle insertion criteria.
- ㉕ DTL: Flow angle deletion criteria.

GROUP 8 – RUN CUTOFF INFORMATION (See Input/Output FORTRAN Symbol Section CUTDAT(1) – CUTDAT(6))

- ㉖ R: Radial coordinate of upper cutoff (units same as R on starting line).
- ㉗ X: Axial coordinate of upper cutoff (units same as X on starting line).
- ㉘ THETA: Angle of upper cutoff line (degrees)
- ㉙ R: Radial coordinate of lower cutoff.
- ㉚ X: Axial coordinate of lower cutoff.
- ㉛ THETA: Angle of lower cutoff line.

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GROUP 9 - TYPICAL LEFT CHARACTERISTIC LINE

- ③④ Characteristic Line: Identifies line for which data is printed.
- ③⑤ Characteristic Point: Identifies point for which data is printed.
- ③⑥ Description: Describes the type of point. The options are:
 - a. input point
 - b. interior point (prints blank)
 - c. wall point
 - d. free boundary point
 - e. shock point
 - f. Prandtl-Meyer point.
- ③⑦ R: Radial distance to the characteristic point.
- ③⑧ X: Axial distance to the characteristic point.
- ③⑨ M: Mach number at the characteristic point.
- ④① Theta: Flow angle at the characteristic point (degrees).
- ④② Entropy: Entropy level at the characteristic point ($\text{ft}^2/\text{sec}^2 - ^\circ\text{R}$).
- ④③ Shock Angle: Shock angle at the characteristic point (only prints when shock point) (degrees).
- ④④ Mach Angle: Mach angle at the characteristic point (degrees).
- ④⑤ Pressure: Static pressure at the characteristic point (psfa).
- ④⑥ Density: Static density at the characteristic point (slugs/ft^3).
- ④⑦ Temperature: Static temperature at the characteristic point ($^\circ\text{F}$).
- ④⑧ Velocity: Velocity of flow at the characteristic point (ft/sec).
- ④⑨ O/F Ratio: O/F ratio at the characteristic point.
- ⑤① Local Mw: Molecular weight at the characteristic point.
- ⑤② Local Gamma: Ratio of specific heats at the characteristic point.
- ⑤③ To*: Normal shock stagnation temperature at the characteristic point ($^\circ\text{R}$).

- (52) P_o^* : Pitot pressure - the normal shock stagnation pressure at the characteristic point (psfa).
- (53) S^* : Normal shock stagnation entropy at the characteristic point ($\text{ft}^2/\text{sec}^2 - ^\circ\text{R}$).
- (54) This is a comparison to the mass flow through the throat. The percent change should be near zero; any change is an indication of accumulated error in the calculation. For a plume this is a comparison to the mass flow at the nozzle exit. The percent change will approach 100% as the characteristic lines start further away from the exit plane. The mass flow printed out after the first characteristic line is in lb/sec if the units of the flow field are in feet. If the flow field is in inches then divide the printed out value by 144 to get lb/sec.
- (55) This is a calculation of the components of net momentum thrust and pressure thrust at the particular wall point in the nozzle.
- FORCEX: Net force in the axial direction (lb_f)
- FORCEY: Net force in the radial direction. For an axisymmetric nozzle FORCEY will be zero (lb_f)
- TORQZ: The net moment produced by the axial and radial forces about the origin of the plume (ft-lb_f)
- DELFX: Incremental force in axial direction (lb_f)
- DELFY: Incremental force in radial direction (lb_f)
- ISPVAC: The vacuum specific impulse ($\text{lb}_f\text{-sec}/\text{lb}_m$)
- CF-VAC: The vacuum thrust coefficient.
- (56) ERRORS: and intermediate statement (see Subsection 3.4.2).

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CASE NO. 25

Group 1

2 SAMPLE NOZZLE PLUME - JPL/NOZZLE BALL CURVE FIT

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 3

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 4

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 5

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 6

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group 7

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

[illegible]

Group 7 [22] 300000+00-01+ 23 000000 24 MESH CONTROL CRITERIA 25 000000 26 000000 27 000000
 SAMPLE NOZZLE PLUME - JPL/NOZZLE BALL CURVE FIT
 8 [28] 50000+02 29 UPPER BOUNDARY 30 1M1A 31 00000 32 LOWER BOUNDARY 33 50000+02 34 00000+02
 RUN CUTOFF INFORMATION

DATE 040170 PAGE 27
 CASE NO. 25 PAGE 3

CASE NO. 25		DATE 040170		PAGE 33	
LINE POINT DESCRIPTION		34 35 36		PAGE 9	
SAMPLE NOZZLE PLUME - JPL/NOZZLE BALL CURVE FIT					
43 R		44 PRESSURE		45 DENSITY	
46 LOCAL MW		47 LOCAL SAMA		48 THETA	
49 INPUT POINT		50 LOCAL SAMA		51 TO	
52		53		54	
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406		407			

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3.5.2 Statements from Subroutine Errors (Output)

1. Illegal crossing of right-running characteristics; run is continued with point deleted.

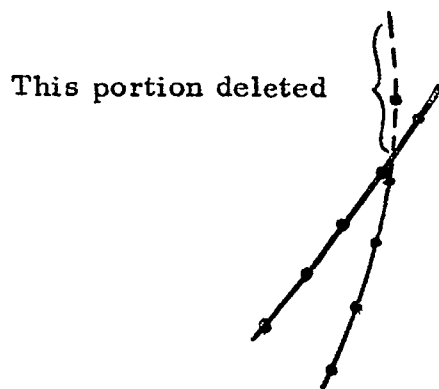
This statement occurs when the newly calculated characteristic point falls below the right-running characteristic line formed by the two base points.



These points are averaged and the average is used to replace the crossed points.

2. Illegal crossing of left-running characteristics; run is continued with remainder of line deleted.

This statement occurs when the new left-running characteristic line crosses the previous left-running characteristic line.



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3. Previously noted errors have propagated to lower boundary or problem limits have been reached. Case terminated.

The program has terminated properly, a shock has intersected the axis of symmetry, the problem limits set by the user have been reached or an error in the mesh construction which occurred somewhere in the field has propagated to the lower boundary.

4. Lower boundary solution will not converge.

Program is unable to obtain a solution at lower boundary within a preset number of iterations.

5. Interior solution will not converge.

Program is unable to obtain a solution at an interior point within a preset number of iterations.

6. Upper boundary solution will not converge.

Program is unable to obtain a solution at the upper boundary within a preset number of iterations.

7. Shock solution will not converge. Line terminated.

The program is unable to satisfy both oblique shock relations and flow field properties simultaneously within a specified number of iterations.

8. ITSUB WNC in RGMOFP

Real gas solution of Mach number as a function of pressure will not converge in the preset number of iterations.

9. ITSUB WNC in RGVOFM

Real gas solution of velocity as a function of Mach number will not converge in the preset number of iterations.

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10. ITSUB WNC in THETPM

Unable to balance the last Prandtl-Meyer point pressure with back pressure at free boundary or flow angle at last point with flow angle at solid boundary within the preset number of iterations.

11. ITSUB WNC in AOASTR

Unable to balance the mass flow at A/A^* with mass flow at throat within the preset number of iterations.

12. MOCSOL WNC

The characteristic solution for a new point is unable to be reached within the preset number of iterations.

13. SHOCK has problem

This statement indicates that subroutine (SHOCK) is unable to reach a solution. (SHOCK) will reinitiate the solution and try again in most cases. When this statement is printed out there will also be a 2, 3, 4, 5, 6 or 7 written out from (SHOCK) which will indicate the type of problem.

2	the shock solution will not converge
3	the shock has intersected the axis
4 and 5	not presently used
6	insufficient downstream information - call again with appropriate option
7	insufficient downstream information - call again with appropriate option

14. ITSUB WNC in TURN

Iteration for shock angle based on known turning angle cannot obtain convergence within specified number of iterations.

15. ITSUB WNC in OVEREX

Iteration for obtaining shock angle by balancing downstream pressure to back pressure is unable to converge within preset number of iterations.

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16. The following case cannot be found on Master Tape

The program is unable to find the desired gas case among the cases present on the Master Tape.

17. ITSUB WNC in HYPER

Unable to balance the pressure at the expansion corner with the pressure at the pressure boundary within the present number of iterations.

18. ESHOCK WNC

Iterative solution of conservation equations across a shock would not converge within the preset number of iterations.

19. ITSUB WNC in MASCON

Iteration for Mach number distribution using conservation of mass flow would not converge within the preset number of iterations.

20. Subsonic Mach number encountered.

The method of characteristics solution is unable to handle subsonic Mach numbers because of the use of the term $\sqrt{M^2 - 1}$. When this error is encountered it is usually the result of the propagation of some upstream error.

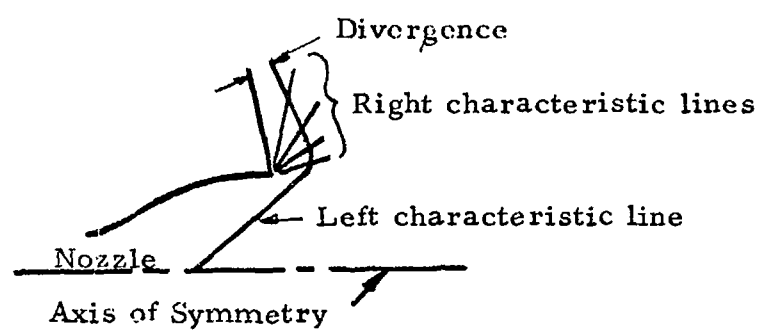
21. Negative velocity encountered.

The initial guess for an iterative solution was bad which resulted in a negative velocity. May also have resulted from some error in the boundary conditions.

22. Characteristic lines diverge, line terminated.

Unable to find a new characteristic point because of a very small difference in angle between two characteristic lines. (See figure on following page.)

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3.6 SAMPLE PROBLEM

Below is a listing of the sample problem.

Card 1	S-IV TESTS RL-10 ENGINE PR/PC=60.F-5															
Card 2	1	10	21	1019	1	0	1	0113	0	0	11	0	0	20	01	0
Card 3a	0.45	0.3	0.0	0.0	0.0	0.3	0.445									
Card 3b	0.1	0.325	0.2	0.375	0.3	0.445										
Card 3c	0.4	0.515	0.5	0.58	0.75	0.725										
Card 3d	1.0	0.86	1.25	0.980	1.50	1.085										
Card 3e	1.75	1.182	2.0	1.28	2.25	1.365										
Card 3f	2.5	1.445	3.0	1.59	3.50	1.712										
Card 3g	4.0	1.83	4.29	1.89												
Card 3h	3	0	30.24													1000.
Card 3i	2	0														1000.
Card 4	S-IV TESTS -02/H2-PREL MKS 1 2															
Card 5	5.0															
Card 6a	0.0 12															
Card 7a	0.000	11.558	1.14376	3330.81	23.815995											
Card 7b	1.000	11.691	1.14578	3141.66	13.698737											
Card 7c	1.759	11.899	1.15768	2784.51	4.763109											
Card 7d	2.148	11.995	1.17286	2544.81	2.381599											
Card 7e	3.330	12.094	1.23567	1732.25	0.238160											
Card 7f	4.237	12.096	1.26618	1254.56	0.047632											
Card 7g	4.656	12.096	1.28029	1084.45	0.023816											
Card 7h	5.749	12.096	1.31156	760.09	0.004763											
Card 7i	6.363	12.096	1.32398	674.19	0.002382											
Card 7j	7.888	12.096	1.34329	426.53	0.000476											
Card 7k	8.710	12.096	1.34937	353.83	0.000238											
Card 7l	10.834	12.096	1.35837	232.94	0.000048											
Card 6b	1.46	12														
Card 7m	0.000	10.668	1.09641	2466.16+6805	-02											
Card 7n	1.000	10.831	1.09525	2389.41+3985	-02											
Card 7o	1.776	11.149	1.09457	2241.21+1361	-02											
Card 7p	2.157	11.345	1.09583	2147.54+6805	-03											
Card 7q	3.199	11.906	1.12651	1808.12+6805	-04											
Card 7r	3.853	12.086	1.22804	1452.72+1361	-04											
Card 7s	4.214	12.095	1.26146	1267.39+6805	-05											
Card 7t	5.247	12.096	1.29878	890.26+1361	-05											
Card 7u	5.754	12.096	1.31166	759.05+68	-06											
Card 7v	7.119	12.096	1.33522	516.42+1361	-06											
Card 7w	7.866	12.096	1.34310	428.77+68	-07											
Card 7x	9.779	12.096	1.35478	283.74+1361	-07											
Card 8	0.0	0.0428	1.01	0.0	0.284	5.0										
Card 10	10.0	0.0	0.0	0.0	20.	90.										0.2
Card 11	2.0	0.0	3.0	0.0	10.0	0.0										

Card 1

<u>Cols.</u>	<u>Value</u>	<u>Description</u>
1-72		Header card with title of problem.

Card 2

5	1	ICON(1) - Gas properties will be input from cards.
9	1	ICON(2) - Right running start line.
10	0	ICON(2) - Straight start line with the Mach number given.
14, 15	21	ICON(3) - 21 Start line points
17-20	1019	ICON(4) - The upper boundary will be curve fit by the program using 17 points which describe the nozzle. there will be 19 upper wall systems: One for the nozzle throat, 17 for the nozzle wall and a free boundary equation.
25	1	ICON(5) - There is one lower wall equation.
27-30	0	ICON(6) - Any shock intersecting the lower wall will not be reflected automatically.
35	1	ICON(7) - The problem is an axisymmetric case.
37, 38	01	ICON(8) - After the solution reaches the nozzle lip the output will be full one line data.
39, 40	13	ICON(8) - The output for the nozzle solution up to the lip will be limited, three line data.
41-45	0	ICON(9) - The start line does not contain a shock point.
50	0	Not presently used.
54-55	11	ICON(11) - The case number for the problem is 11.
60	0	ICON(12) - The first shock encountered during the solution will be calculated
65	0	ICON(13) - The viscous boundary layer option for the start line will not be used.

Card 2 (Cont'd)

<u>Cols.</u>	<u>Value</u>	<u>Description</u>
69,70	20	ICON(14) - Any Prandtl-Meyer expansion will be divided into 20 "rays."
75	1	ICON(15) - Mesh control will be utilized.
80	0	ICON(16) - No "debugging" printout during the shock and pitot pressure calculations.

Card 3a

NOTE: 3a - 3g are used because the nozzle wall curve fit option has been selected for the upper boundary of the problem.

1-10	.45	RC - The radius of curvature of the nozzle throat is .45 units.
11-21	.3	RT - The throat radius is .3 units.
31-40	0.0	THETA - The throat divergence angle is 0.0. The throat equation will only be considered up to the minimum area of the nozzle.
31-40	0.0	XO - The nozzle throat equation will not be shifted.

Card 3b

1-10	.1	XIN(1) - Axial location of first point describing nozzle wall.
11-20	.325	YIN(1) - Radial location of first point describing nozzle wall.
21-30	.2	XIN(2)
31-40	.375	YIN(2)
41-50	.3	XIN(3)
51-60	.445	YIN(3)

Cards 3c-3g

These cards contain the coordinates of the rest of the 17 points describing the nozzle wall.

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Card 3h

<u>Cols.</u>	<u>Value</u>	<u>Description</u>
1	3	IWALL - The last upper boundary equation is a free boundary equation.
5	0	ITRANS - No discontinuity follows this boundary.
11-20	30.24	PINF - The nozzle will expand to a free boundary back pressure of 30.24 psfa.
61-70	1000.	XMAX - The maximum axial coordinate for which this equation applies is 1000. units.

Card 3i

1	2	IWALL - The lower wall equation is a polynomial equation.
5	0	ITRANS - No discontinuity follows this equation.
11-60	0.0	WALLCO(1)-(5) - The lower boundary equation is a straight line with zero slope passing through the origin of the system.
61-70	1000.	XMAX - The maximum axial coordinate for which this equation applies is 100 units.

Card 4

1-24	S-IV Tests -02/H2 PREL	ALPHA - Gas name and description.
30-32	MKS	UNITS - The gas data is input in metric units.
40	1	IOF - There is 1 O/F table of gas data.
45	2	IS - There are two entropy tables containing gas data.

Card 5

1-10	5.0	OFRAT - The O/F ratio for this data is 5.0.
------	-----	---

Card 6a

1-10	0.0	STAB(1) - The entropy level of the first entropy table.
------	-----	---

Card 6a (Cont'd)

<u>Cols.</u>	<u>Value</u>	<u>Description</u>
19-20	12	IVTAB - There are 12 velocity or Mach number "cuts" of data in this entropy table.

Card(s) 7a

1-10	0.0	TAB(I,J,K,1) - Mach number for the first Mach number cut in the entropy table.
11-20	11.558	TAB(I,J,K,2) - Molecular weight of the gas at this Mach number. If the units on Card 4 were ENG then this should be the gas constant R.
21-30	1.14376	TAB(I,J,K,3) - GAMMA for the gas at this Mach number.
31-40	3330.81	TAB(I,J,K,4) - Static temperature at this Mach number, °K.
41-50	23.815995	TAB(I,J,K,5) - Static pressure at this Mach number, Atmospheres.

Cards 7b-7l

These cards contain similar information to that on Card 7a except corresponding to different Mach number "cuts."

Card 6b

1-10	1.46	STAB(2) - The entropy level of the second entropy table (cal/gram-°K)
19-20	12	IVTAB - There are 12 velocity or Mach number "cuts" of data in this entropy table.

Cards 7m-7x

These cards contain similar data as Cards 7a-7l except that this data was generated for an entropy level corresponding to 1.4 cal/gram-°K.

Card 8

1-10	0.0	CORLIP(1) - The axial coordinate of the upper limit of the start line is 0.0.
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Card 8 (Con'd)

<u>Cols.</u>	<u>Value</u>	<u>Description</u>
11-20	.0428	CORLIP(2) - The axial coordinate of the lower limit of the start line is .0428 units.
21-30	1.01	CORLIP(3) - The Mach number of the flow along the start line.
31-40	0.0	CORLIP(4) - There is zero entropy level at the start line.
41-50	.284	STEP(5) - The area of the nozzle throat.
51-60	5.0	CORLIP(5) - The O/F ratio along the start line.
61-70	0.0	STEP(6) - The program will set the minimum ΔP for discontinuing shock calculations at .001.

Card 10

1-10	100.	CUTDAT(1) - The maximum radial coordinate considered for this problem will be 100. units at the upstream cutoff point.
11-20	0.0	CUTDAT(2) - Each characteristic line will cut off for any axial value less than 0.0.
21-30	0.0	CUTDAT(3) - The angle the upper cutoff makes with the horizontal is 0.0.
31-40	0.0	CUTDAT(4) - The minimum radial coordinate considered for this problem will be 0.0 at the downstream cutoff point.
41-50	20.0	CUTDAT(5) - The maximum axial coordinate for which calculations will be made.
51-60	90.0	CUTDAT(6) - The angle the downstream cutoff line makes with the horizontal is 90.0 degrees.
61-70	.2	STEP(3) - Anytime the axial distance between two characteristic lines exceeds .2 units a new left running characteristic line will be started.

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Card 11

<u>Col(s)</u>	<u>Value</u>	<u>Description</u>
1-10	2.0	DIV(1) - Maximum change in absolute length between any two adjacent characteristic points is 2.0 units.
11-20	0.0	DIV(2) - No points will be deleted because of the minimum change in absolute length.
21-30	3.0	DIV(3) - Maximum change in Mach number between any two consecutive characteristic points is 3.0.
31-40	0.0	DIV(4) - No points will be deleted because of the minimum change in Mach number.
41-50	10.0	DIV(5) - Maximum change in flow angle between any two consecutive characteristic points is 10°.
51-60	0.0	DIV(6) - No points will be deleted because of the minimum change in flow angle.

Section 4

REFERENCES

1. Prozan, R.J., "Development of a Method-of-Characteristics Solution for Supersonic Flow of an Ideal, Frozen or Equilibrium Reacting Gas Mixture," LMSC-HREC A782535, Lockheed Missiles & Space Company, Huntsville, Ala., April 1966.
2. Gordon, S., and B.J. McBride, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks and Chapman-Jouguet Detonations," NASA SP-273, NASA-Lewis Research Center, Cleveland, Ohio, 1971.
3. Smith, S.D., "Description of the Method of Characteristics Radial Plot Program," (to be published).

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Appendix
SOLUTION TECHNIQUES

A-1

Appendix

MESH CONSTRUCTION FOR INTERNAL FLOW

The calculations described previously are point or small region solutions. Some process must be defined which successively employs the proper calculation at the proper time in order to describe the entire field. In order to facilitate a description of the mesh construction process let Φ represent the total knowledge of flow properties at a point in the field. Also let the expression

$$\Phi = \Psi(\Phi_1, \Phi_2, \dots, \Phi_m)$$

stand for properties at a new point which are computed as a function Ψ of (m) other points. There will be basically six such functional operations $\Psi_O, \Psi_I, \Psi_B, \Psi_{As}, \Psi_s, \Psi_{pM}$, which stand for input point, interior point, boundary point, attached shock point, shock, and Prandtl-Meyer points. In addition the superscript (u) will indicate that the operation is to be performed in the presence of an upper boundary while (L) indicates a lower boundary.

Due to the complexity of handling multiple shock waves, a single shock wave restriction will be imposed. This shock wave is arbitrarily chosen to be of the right running family. This type of problem will most frequently occur in cases of interest. If a left running shock wave occurs the problem is simply inverted.

The choice of right running shock waves also dictates that left running characteristic lines be followed in the calculation. This allows one to retain a minimum of information, i. e., a known characteristic line (hereafter referred to as (j)) and a line in the process of being computed (k).

To begin the problem all necessary boundary conditions must, of course, be supplied. In addition a starting line containing N points which are designated ψ_n ($n = 1, \dots, N$) must be supplied.

Figure A-1 illustrates a flow field in which there are no discontinuities and in which the mesh construction is terminated when the region of interest has been computed.

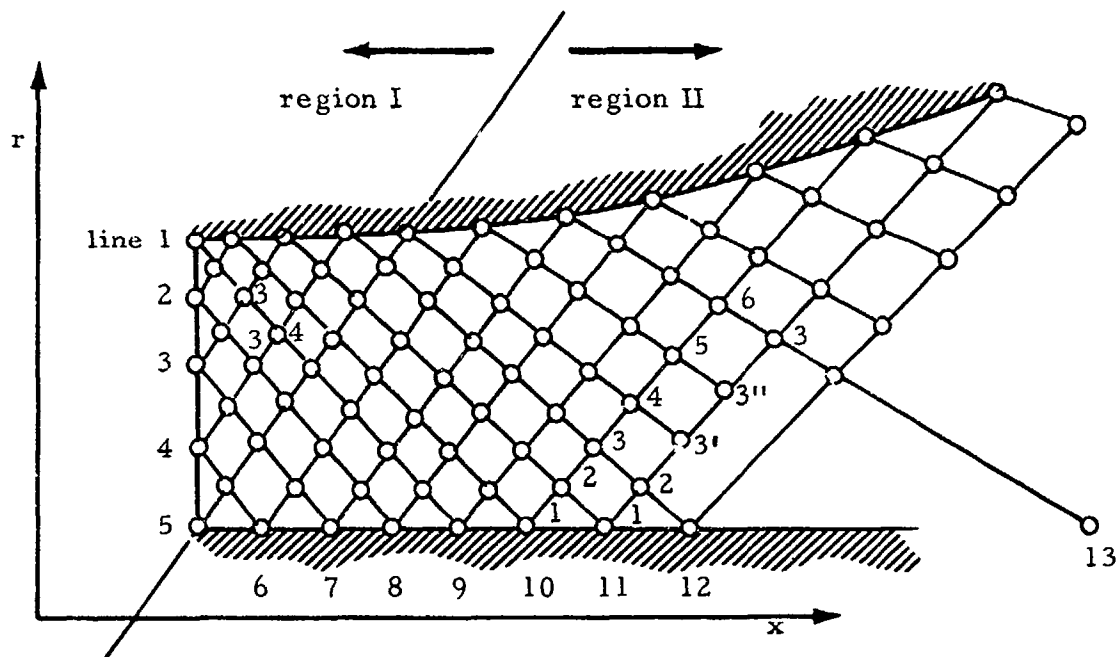


Figure A-1

In region I the left running characteristic lines initiate as input points and the mesh construction may be described by;

$$\phi_{i,k} = \begin{cases} \psi_0(\phi_n) & i = 1 \\ \psi_I(\phi_{i-1,k}, \phi_{i-1,j}) & i = 2 \dots (2n-2) \\ \psi_B^u(\phi_{i-1,k}, \phi_{i-2,j}) & i = 2n-1 \end{cases} \quad (A-1)$$

where n varies from 1 to N and $\phi_{i,k}$ represents the flow properties at the i^{th} point on the k line. For instance, in calculating the fourth point on the fourth line shown in the figure, line three is known in its entirety and line four up to and including the third point is known. The above set of relations says that point three on line four and point three on line three will determine, through the interior point solution, the next point (four) on line four.

For region II we have;

$$\phi_{i,k} = \begin{cases} \psi_B^L(\phi_{1,j}, \phi_{2,j}) & i = 1 \\ \psi_I(\phi_{i-1,k}, \phi_{i+1,j}) & i = 2, \dots, (2N-2) \\ \psi_B^u(\phi_{i-1,k}, \phi_{i,j}) & i = 2N-1 \end{cases} \quad (A-2)$$

As a new line becomes completely defined it may be referred to as j and the process continued indefinitely.

It is possible to combine regions (1) and (2) into a more general scheme if a variable i_N is defined which takes on the value (1) in region I and (0) in region II. At this time the number of points on the j line (i_{T_j}) and the number of points on the new line (i_{T_k}) are defined. Then;

$$\phi_{i,k} = \begin{cases} i_N \psi_O(\phi_n) + (1-i_N) \psi_B^L(\phi_{1,j}, \phi_{2,j}) & i = 1 \\ \psi_I(\phi_{ik,k}, \phi_{ij,j}) & \begin{matrix} ik = i-1 \\ ij = i-2i_N+1 \end{matrix} \\ \psi_B^u(\phi_{ik,k}, \phi_{ij,j}) & \begin{matrix} ik = i-1 \\ ij = i-2i_N \end{matrix} \end{cases} \quad \left. \begin{matrix} i = 2, \dots, i_{T_k} - 1 \\ i = i_{T_k} \end{matrix} \right\} \quad (A-3)$$

but

$$i_{T_k} \leftarrow i_{T_j} + 2i_N$$

A-3

Obviously i_{T_j} would have been initialized to (-1) prior to the start of the calculation. When the line is finished i_{T_j} is set to the current value of i_{T_k} .

Thus the process for computing the entire flow field for such a simplified case is described by the set of expressions (A-3). In general, however, discontinuities will arise so that a more flexible description is necessary. If, by some process, points were discarded from the (j) and (k) arrays and the number of points lost is i_{δ_j} and i_{δ_k} respectively then (A-3) becomes;

$$\phi_{i,k} = \begin{cases} i_N \psi_o(\phi_n) + (1-i_N) \psi_B^L(\phi_{1,j}, \phi_{2,j}) & i = 1 \\ \psi_I(\phi_{ik,k'}, \phi_{ij,j}) & \begin{matrix} ik = i-1 \\ ij = i-2i_N+1+\tilde{i}_{\delta_j}+\tilde{i}_{\delta_k} \end{matrix} \\ \psi_B^u(\phi_{ik,k'}, \phi_{ij,j}) & \begin{matrix} ik = i-1 \\ ij = i-2i_N+\tilde{i}_{\delta_j}+\tilde{i}_{\delta_k} \end{matrix} \end{cases} \quad \begin{matrix} i = 2, \dots, i_{T_k}-1 \\ i = i_{T_k} \end{matrix} \quad (A-4)$$

but

$$i_{T_k} \leftarrow i_{T_j} + 2i_N - i_{\delta_j} - i_{\delta_k}$$

where the tilda over i_{δ_j} and i_{δ_k} indicates that current values are to be used. These variables are reset to zero at the beginning of each new line.

To illustrate this, imagine that points (1) and (2) have been computed on line 11 and that after point(3') had been computed in the normal fashion it was necessary to discard it. The next point to be computed would then be (3'') but if for some reason it was necessary to discard point 5 on the (j) line then the point (3'') would not exist. Therefore a point has been deleted on each line ($\tilde{i}_{\delta_j} = \tilde{i}_{\delta_k} = 1$) and the diagram and the set of equations (4) indicate that point (6) on line (j) and point (2) on line (k) would be used in the computation of (3) on line (k).

It is now possible to include a shock wave into the logic scheme. Since it is a mathematical requirement that characteristic lines of the same family as the shock are continuously intercepted by it, the ability to discard points was necessary. If this was the only mechanism for discarding points then the logic process would be;

$$\phi_{i,k} = \left\{ \begin{array}{ll} i_N \psi_O(\phi_n) + (1-i_N) \psi_B^L(\phi_{1,j}, \phi_{2,j}) & i = 1 \\ \psi_I(\phi_{ik,k}, \phi_{ij,j}) \quad \left. \begin{array}{l} ik = i-1 \\ ij = i-2i_N+1 \end{array} \right\} & i = 2, \dots, i_{s_k} \\ \psi_S(\phi_k, \phi_j) \quad \left. \begin{array}{l} i = i_{s_k} - i_{\delta_k} \\ i = i_{s_k} - i_{\delta_k} + 1 \end{array} \right\} & \\ \psi_I(\phi_{ik,k}, \phi_{ij,j}) \quad \left. \begin{array}{l} ik = i-1 \\ ij = i-2i_N+1+i_{\delta_k}+i_{\delta_j} \end{array} \right\} & i = i_{s_k} - i_{\delta_k} + 2, \dots, i_{T_k} - 1 \\ \psi_B^u(\phi_{ik,k}, \phi_{ij,j}) \quad \left. \begin{array}{l} ik = i-1 \\ ij = i-2i_N+i_{\delta_k}+i_{\delta_j} \end{array} \right\} & i = i_{T_k} \end{array} \right. \quad (A-5)$$

where

$$i_{T_k} \Leftarrow i_{T_j} + 2i_N - i_{\delta_j} - i_{\delta_k}$$

and where i_{s_k} is defined in much the same fashion as i_{T_k} , which is;

$$i_{s_k} \Leftarrow i_{s_j} + 2i_N - 1$$

where i_{s_j} is the location of the upstream shock point on the (j) line.

Figure A-2 illustrates the mesh construction when a shock wave is present.

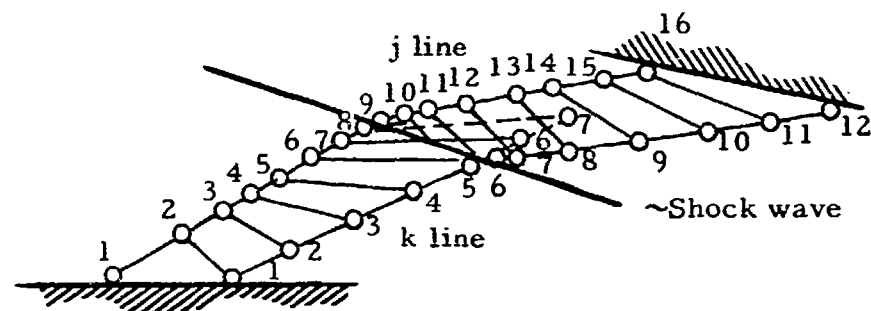


Figure A-2

In this example $i_N = 0$ and $i_{s_j} = 8$ so that $i_{s_k} = 7$. Also $i_{T_j} = 16$ so that i_{T_k} would normally also be 16. The (k) line is computed up to point 7 and the shock solution is then employed. In this case the shock solution finds that three points of the (k) line fall downstream of the shock (minimum is one) while two right running lines (points 10 and 11 on the (j) line) also are intercepted by the shock wave. Thus in this example $i_{\delta_k} = 2$ and $i_{\delta_j} = 2$. The set of equations (A-5) then says that the double shock point should be points 5 and 6 on the (k) line and that the total number of points on the (k) line has decreased to 12. Note also that the value of i_{s_j} to begin the next line must be change to 5.

So far no mention of how the shock wave begins has been made. There are two types of shock waves considered; the attached shock wave

which arises due to the flow being forced to negotiate a compression corner on the upper boundary, and the envelope shock. The first of these is easily detected from the boundary conditions and is initially of finite strength. The second type is detected by a mathematical discontinuity in the mesh construction (crossing of right running lines) and is initially of zero strength i.e., a Mach wave. An example of the compression corner solution is given in Figure A-3.

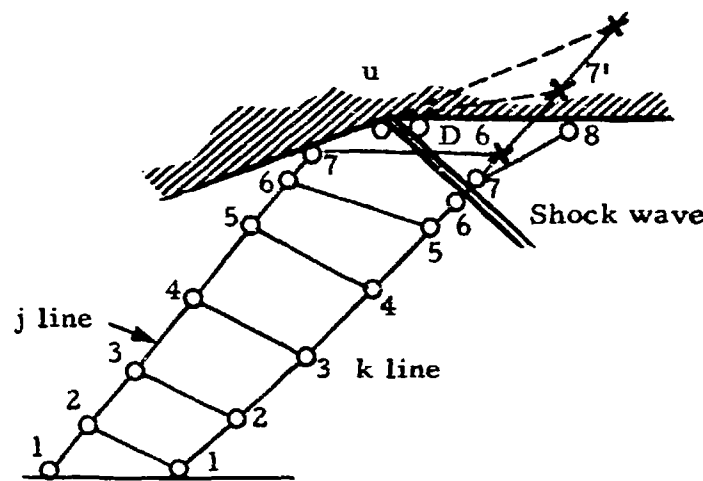


Figure A-3

The computation of the (k) line is completed without any prior knowledge that a compression corner exists. A check is made after the boundary solution and the boundary information indicates that a compression corner must be treated. A linear interpolation is performed between the boundary point on line (j) and the fictitious boundary point on line (k) in order to determine the flow properties at point u. An oblique shock calculation is made where the turning angle is known. Using this point and point 6 ($i_{T_k} - 1$) a new virtual point ($7'$) is computed. i_{s_k} is set to i_{T_k} and the shock solution illustrated in Fig. A-4 is employed. This shock solution completes the (k) line in the proper fashion. In this example $i_{T_j} = 6$ and the next line is computed as previously discussed.

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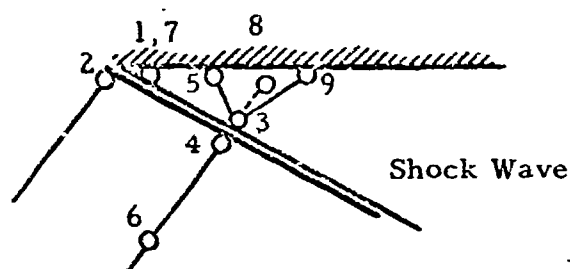


Figure A-4 - Solid or Free Upper Wall Interacting with Reflected Shock Wave or Attached Shock Wave with Insufficient Downstream Information

The envelope shock is detected by a crossing of right running characteristic lines as shown in the figure below.

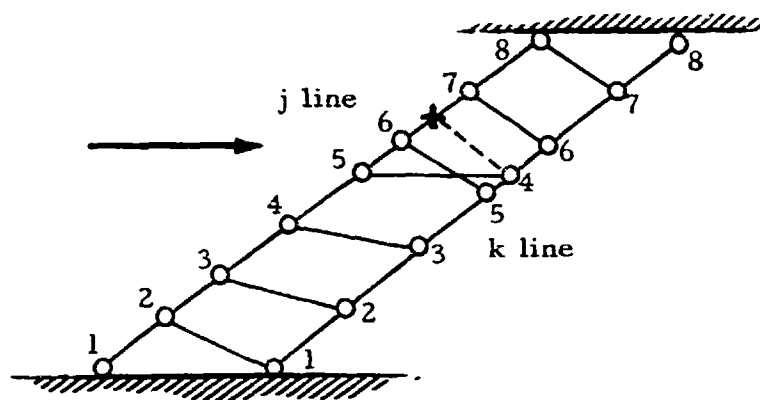


Figure A-5

In this example point (5) on the (k) line is found to fall in a previously described region (the region between points (3) and (4) on the (k) line). This discontinuity in the solution is interpreted as a shock wave. If the grid size were chosen small enough the shock wave would initially be of zero strength. Point (5) on line (j) is chosen to be a point which lies on the shock wave and the shock solution is employed. The results of this solution are stored in the normal fashion on the (k) line. Obviously the only difference between this situation and treatment of a previously developed shock wave is to modify the (j) line such that it appears to the logic scheme as though a shock wave crossed the (j) line at point (5).

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Figure A-6 illustrates the mesh construction in the vicinity of an expansion corner.

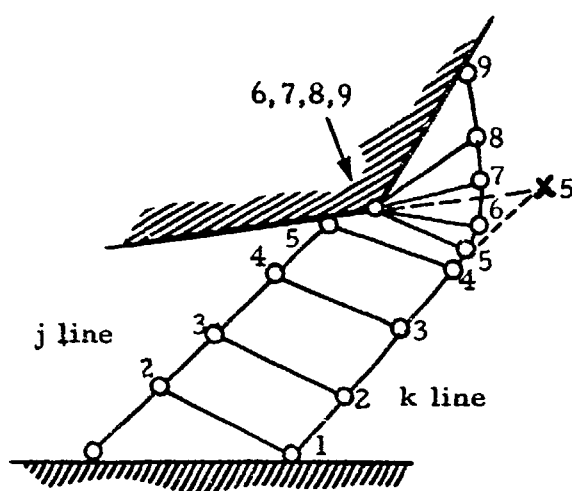


Figure A-6

In this case point (5) on line (k) is expected to be a boundary point. It is discovered however, that an expansion corner must be negotiated by the (k) line. A point (6) on the (j) line is found by interpolation. A Prandtl-Meyer calculation is employed and the fan of points is stored in the (j) line above (6). The total number of points to be expected on the (k) line is increased accordingly and the normal logic scheme will now complete the new line. The next line is calculated in the standard fashion.

An expansion corner on a lower wall is somewhat a more complicated situation. Since the calculation no longer utilizes the input line, the lower wall expansion fan may be stored in this area. The set of relations, Equation (A-5) is modified to that of Equation (A-6).

$$\phi_{ij} = \left\{ \begin{array}{l} i_N \psi_O + (1-i_N) \psi_B^L (\phi_{i,j}, \phi_{2,j}) \\ \psi_I (\phi_{ik,k}, \phi_{ij,j}) \quad \begin{array}{l} ik = i-1 \\ ij = i + (i_\ell - 2) i_N + 1 \end{array} \\ \psi_S (\phi_k, \phi_j) \quad \begin{array}{l} i = i_{s_k} - i_{\delta_k} \\ i = i_{s_k} - i_{\delta_k} + 1 \end{array} \\ \psi_I (\phi_{ik,k}, \phi_{ij,j}) \quad \begin{array}{l} ik = i-1 \\ ij = i + (i_\ell - 2) i_N + i_{\delta_k} + i_{\delta_j} \end{array} \\ \psi_B^u (\phi_{ik,k}, \phi_{ij,j}) \quad \begin{array}{l} ik = i-1 \\ ij = i + (i_\ell - 2) i_N + i_{\delta_k} + i_{\delta_j} \end{array} \end{array} \right\} \quad \begin{array}{l} i = 2, \dots, i_{s_k} \\ i = i_{s_k} - i_{\delta_k} + 2, \dots, i_{T_k} - 1 \\ i = i_{T_k} \end{array}$$

where

$$i_{T_k} \Leftarrow i_{T_j} + (2-i_\ell) i_N - i_{\delta_j} - i_{\delta_k}$$

and where

$$i_{s_k} \Leftarrow i_{s_j} + (2-i_\ell) i_N - 1$$

for which $i_\ell = i_N = 1$ until all fan points are used up.

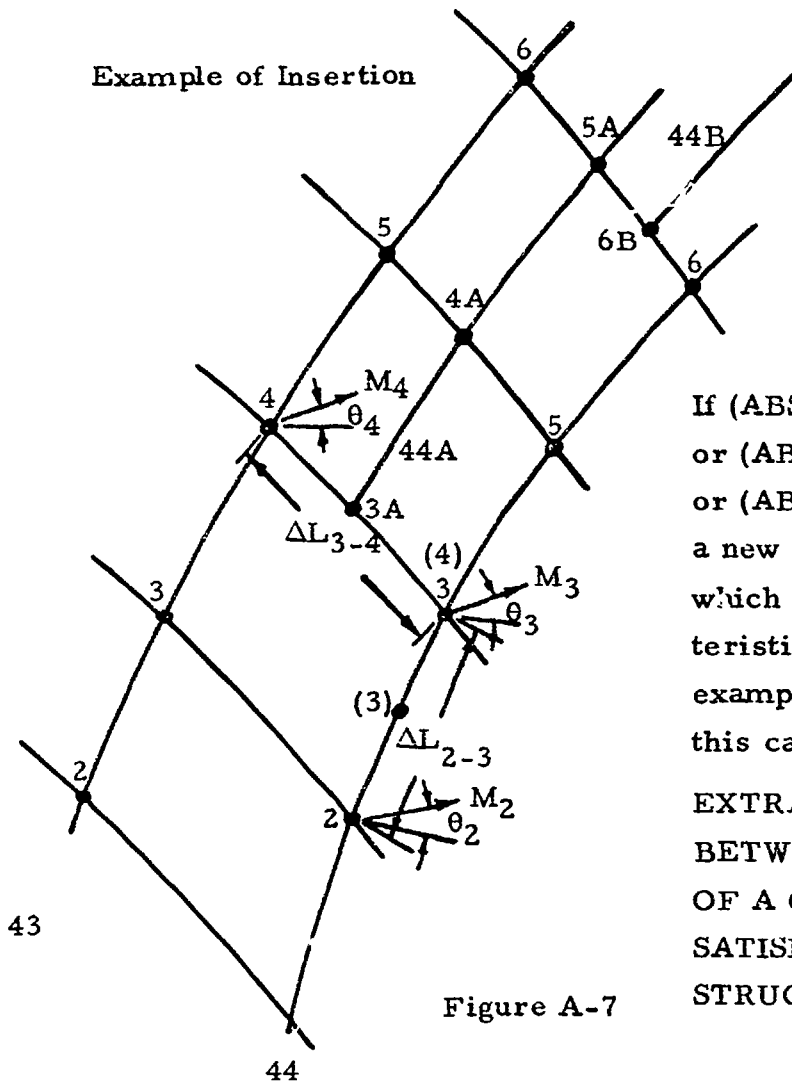
Mesh Control

The mesh control utilized by the program is a means of controlling the minimum and maximum changes in distance, Mach number and flow angle between any two consecutive characteristic points on both left and right running characteristic lines. The advantage of mesh control occurs in plumes and nozzles where a great deal of expansion is encountered. The characteristic mesh size expands to a degree where large spaces may be encountered in the plume and insufficient data is present.

Mesh control is employed by checking on the absolute difference in Mach number and flow angle and the distance between two points. These checks are made between both the left and right running base points and the newly calculated characteristic point. If these differences do not satisfy the input criteria the new point will either be deleted or another pointed added. The fixed point equations and counting schemes within the program are altered to account for points which are added and deleted.

The following two figures are examples of insertion and deletion of points as a result of mesh control criteria.

Example of Insertion



If $(ABS(\theta_4 - \theta_3))$ is greater than $DIV(5)$
 or $(ABS(M_4 - M_3))$ is greater than $DIV(3)$
 or $(ABS(\Delta L_{3-4}))$ is greater than $DIV(1)$
 a new left running point 3A is added
 which starts a new left running charac-
 teristic line. The following is an
 example of the message printed out for
 this case:

EXTRA LRC NO. 1 HAS BEEN ADDED
 BETWEEN LINES 43 AND 44 BECAUSE
 OF A CHANGE OF .20468+00 DID NOT
 SATISFY THE DISTANCE MESH CON-
 STRUCTION BETWEEN POINTS 4 AND 3.

Figure A-7

If $(ABS(\theta_3 - \theta_2))$ is greater than $DIV(5)$
 or $(ABS(M_3 - M_2))$ is greater than $DIV(3)$
 or $(ABS(\Delta L_{2-3}))$ is greater than $DIV(1)$
 a new right running point 3 will be added between point 2 and old point 3. Old
 point 3 then becomes point 4. The following is an example of the message printed
 out for this case:

A NEW RRC HAS BEEN ADDED BETWEEN POINTS 2 AND 3 ON LINE
 44 BECAUSE A CHANGE OF .20140+00 DID NOT SATISFY THE FLOW
 ANGLE MESH CONSTRUCTION.

It is possible for more than one left running characteristic to be added as shown
 when a new left running point 6B was added between points 5A and 6 on line 44A
 and 44.

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Example of Deletion

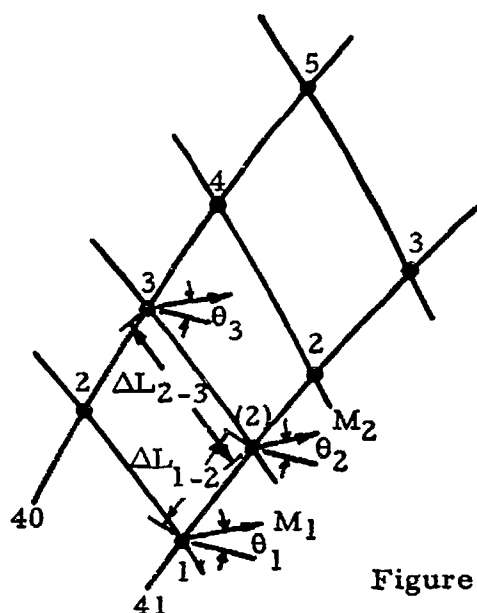


Figure A-8

If $(\text{ABS}(\theta_3 - \theta_2))$ is less than $\text{DIV}(6)$

or $\text{ABS}(\theta_2 - \theta_1)$ is less than $\text{DIV}(6)$

or $\text{ABS}(M_3 - M_2)$ is less than $\text{DIV}(4)$

or $\text{ABS}(M_2 - M_1)$ is less than $\text{DIV}(4)$

or $\text{ABS}(\Delta L_{1-2})$ is less than $\text{DIV}(2)$

or $\text{ABS}(\Delta L_{2-3})$ is less than $\text{DIV}(2)$

point (2) is deleted and a new point 2 is calculated using point 4 on line 40 and point 1 on line 41.

The following message will occur for this example:

THE POINT 2 ON LINE 41 HAS BEEN DELETED BECAUSE A
CHANGE OF 1.5 DID NOT SATISFY THE MACH NUMBER MESH
CONSTRUCTION.

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Automatic Shock Reflection

The method of automatically reflecting a shock begins when the shock intersects the axis of symmetry. The downstream shock point and the last point on a specified boundary equation are connected with a straight line. The flowfield is then searched for flowfield properties which fall at certain points on the line as determined from the number of specified number starting line points. If no point is located which falls on the line, an interpolation is performed to determine the flowfield properties at the point. Once the specified number of points are found the properties at each point are stored in the starting line array. The problem and boundary equation are then inverted and the problem is reinitiated.

Viscous Start Line Option

The viscous start line option is for use in setting up a supersonic viscous one-dimensional start line at a nozzle exit plane. Subroutine VISCOUS is called with N, the inverse of the power of the profile, NBL, the number of points to be calculated in the viscous portion of the start line, XL, the characteristic length (ft. - usually the nozzle wall length) and CU, a conversion factor for converting the characteristic length XL into the units of the flow field.

A flat plate boundary layer formulation was used to determine the boundary layer properties. Since the local flow properties vary greatly through the boundary layer of supersonic flow an average value of pertinent flow properties should be determined. A reference temperature obtained by Equation 1 (Ref. 1) is used to determine

$$T_{ref} = T_{ex} + .5 (.9T_o - T_{ex}) + .22 (T_o - T_{ex}) \quad (1)$$

an average viscosity, where the viscosity is obtained from Equation 2.

$$\mu = (2.27 (T_{ref}^{1.5}) 10^{-8}) / (T_{ref} + 198.6) \quad (2)$$

Using these reference conditions a local Reynolds number per foot is obtained using Equation 3.

$$R_e = P_{ex} V_{ex} XL / \mu RT_{ref} \quad (3)$$

The Reynolds number determined from Equation 3 is checked to determine if the boundary layer is laminar or turbulent. A Reynolds number less than 1 million is laminar and a Reynolds number greater than 1 million is turbulent.

Once the flow regime has been determined it is then necessary to determine the boundary layer thickness. The boundary layer thickness is taken as that

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distance from the surface at which the local velocity reaches 99 percent of the free stream velocity. Equations 4 and 5 are used to determine the boundary layer thicknesses of a laminar or turbulent boundary layer, respectively.

$$\delta_L = 5.2 XL*CU/R_e^{.5} (1 + .732FL) \quad (4)$$

$$\delta_T = .0188 XL*CU*M_e^{1.25} (1 + .176F)/R_e^{.14} \quad (5)$$

FL and F are terms used to adjust the boundary layer thickness depending on whether or not the nozzle is two-dimensional or axisymmetric.

After the boundary layer thickness has been determined the subsonic portion of the boundary layer is eliminated from the calculated thickness. The starting line points (NBL) are then distributed through the boundary layer using an empirical equation of the form of Equation 6 (Ref. 2).

$$\frac{v}{v_{ex}} = \left(\frac{y}{\delta_{el}} \right)^{1/N} \quad (6)$$

N is assumed to be a 2 if the boundary layer is laminar. If the boundary layer was found to be turbulent the value of N input by the programmer is used, (N = 7 to 9).

After the boundary layer points are distributed through the boundary layer they are transferred to a right running characteristic and the rest of the start line points are adjusted to the edge of the boundary layer.

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Symbols for Viscous Start Line Option

CU	-	Conversion factor
FL	-	1 for axisymmetric nozzle, 0 for two-dimensional nozzle
F	-	0 for axisymmetric nozzle, 1 for two-dimensional nozzle
M_e	-	Mach number at edge of boundary layer
N	-	Reciprocal of the exponent of the profile
P_{ex}	-	Static pressure through the boundary layer
R	-	Gas constant
R_e	-	Local Reynolds number
T_o	-	Total temperature at edge of boundary layer
T_{ref}	-	Eckert's reference temperature
v	-	local velocity
V_{ex}	-	Velocity at edge of boundary layer
XL	-	Nozzle wall length - ft.
y	-	Distance from nozzle wall
δ_L	-	Laminar boundary layer thickness
δ_T	-	Turbulent boundary layer thickness
δ_{el}	-	Boundary layer thickness with subsonic portion eliminated
μ	-	Reference viscosity

References for Viscous Start Line Option

1. Eckert, E. R., "Survey of Heat Transfer at High Speeds," WADC 54-70, Wright Air Development Center, April 1954.
2. Schlechting, H., "Boundary Layer Theory," McGraw-Hill Book Company, Inc., New York, New York, 1960.